Southern Ecosystem Health and Productivity in a Changing Environment

A Strategic Plan for Research in the Southern United States

United States Department of Agriculture
Forest Service

Southeastern Forest Experiment Station

Southern Forest Experiment Station

Southern Region

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Supported by:

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PREFACE

The issues of global climate change and the effects of air pollution on ecosystems are on the priority list for many Federal and state agencies, as well as for the University community and for industry. The intent of this Strategic Plan is to provide a framework for all of these efforts within the southern region; serving as a guide for forestry research and application which can be used by many agencies. The USDA Forest Service, through the Southeastern Forest Experiment Station, has taken the lead in developing a plan. We hope this Strategic Plan identifies the major scientific issues, provides the structure to integrate the various research efforts both within and external to the Forest Service, and leads to application of research results within the southern region.

The idea of developing a region-wide Strategic Plan in consultation with various universities, scientists from other federal agencies, and the forest products industry was initiated as Forest Service scientists began preparations for the FY91 budget cycle. The scientists recognized that to initiate research in the region without consideration of the existing Projects related to air pollution and forestry under NAPAP or the planned projects being developed by EPA, NPS, and other agencies/organizations, would be to ignore an essential base of facilities and scientific expertise. It is not the intent of the Forest Service to control the implementation of all components of the Plan, only those directly funded through the Forest Service budget process. Each agency, industry and university should maintain its own implementation plans within the overall structure provided by this South-wide strategy.

EXECUTIVE SUMMARY

The United States has undergone and will continue to undergo changes in the physical and chemical climate as a result of anthropogenic activities. The anticipated changes due to climate flux are of recent concern to the land managers in the United States, who are responsible for protecting and maintaining forest health and productivity. In acknowledgement of this issue, Public Law 100-521, entitled "Forest Ecosystems and Atmospheric Pollution Research Act of 1988", was recently signed, giving the USDA Forest Service the leadership role "to provide for study and research on the decline of U.S. forest productivity and to determine the effects of atmospheric pollutants on forest environments...."

In response to this mandate and as an outgrowth of the national Forest Atmosphere Interactions/Priority Research Program (FAI/PRP), the Southeastern and Southern Forest Experiment Stations and Region 8 have initiated development of a joint plan for research and monitoring in the South; specifically with the intent of bringing into the planning other agencies (EPA, NPS, DOE) and organizations/institutions which are concerned about climate change and related environmental changes. The proposed Program assumes a 10-year effort, coincident with national planning activities. **The mission is to conduct research and monitoring in the southern region of the United States, to determine the interactive responses among forest ecosystems, atmospheric pollution, and climate change, and to use this knowledge to manage and protect the forest environment and resources.** The scope of the plan considers all aspects of the physical and chemical climate, as they might affect forest ecosystems. Following the FAI/PRP guidelines, research is structured around four major research elements with several sub-areas:

1) Effects of the Atmosphere on Ecosystems
   - Forest Response to a Changing Physical Environment
   - Forest Response to a Changing Chemical Environment
   - Forest Response to Interactive Stresses

2) Effects of Ecosystem Change on the Atmosphere
   - Biogenic Emission of Gases
   - Land Management Influences on the Atmosphere

3) Assessment of Long-Term Changes: Ecosystem Monitoring

4) Prediction of Ecosystem Response: Ecosystem Modeling

Each sub-area has a series of research projects identified, in a priority ranking of I - III. While all areas are important, the Forest Service would not have the lead in all. The purpose of the plan is to identify the linkages among program elements AND the agency or institution that will be focusing in that area. Program management and implementation will be done cooperatively with these other agencies and institutions, with the Forest Service playing the central coordinating role in the area of forest ecosystems.

ACKNOWLEDGEMENTS

The impetus for this plan originated in a meeting on September 7, 1988 of several regional and national research leaders to discuss the future of air pollution and forestry research in the South. Formulation of a joint research strategy for the region was the unanimous recommendation of the more than 25 people who attended. A "Strawman" strategic plan was developed, using input from a small planning committee on October 28th, 1988. The committee consisted of: Stan Barras, Forest Service-Southern Forest Experiment Station; Ann Bartuska and Susan Medlarz, Forest Service-Southeastern Forest Experiment Station; Paul Berrang and Dan Brown, Forest Service-Region 8; Ellis Cowling, North Carolina State University; Phil Dougherty, University of Georgia; and Wayne Haines, International Paper (with written input by Richard Olson, Environmental Protection Agency). The "Strawman" was circulated to over 40 people within the USDA Forest Service, U.S. Environmental Protection Agency, National Park Service, Oak Ridge National Laboratory, forest industry, and universities. In mid-January, a follow-up meeting was held in Atlanta to discuss their comments and recommended revisions to this document. The participants contributed text and extensive commentary, which were used to develop this document. We thank all those who provided comments on the "Strawman", and the first draft, and all those who have continued to encourage multi-disciplinary, multi-institutional research.

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I. INTRODUCTION

In 1990 the National Acid Precipitation Assessment Program's (NAPAP) mandate to determine the effects of sulfur and nitrogen deposition on human health and the environment will end. In order to build on the information base generated through NAPAP, the USDA Forest Service, the U.S. EPA, forest industry, universities, and other agencies and institutions are developing plans for future research that capitalizes on NAPAP efforts, but expands the focus to multiple stresses on ecosystems. All parties have agreed to continue the effective working relationships which formed during NAPAP, by developing a regional, interagency strategy for future research and monitoring with input from all interested parties. Under the recently signed Public Law 100-521 entitled "Forest Ecosystems and Atmospheric Pollution Research Act of 1988", the Forest Service has the leadership role "to provide for study and research on the decline in United States forest productivity and to determine the effects of atmospheric pollutants on forest environments . . . ." Enactment of this law is a clear signal that we have only begun to study and evaluate the linkage between air quality and forest health.

The accomplishments of NAPAP, and other environmental research programs, have demonstrated the importance of looking at the interactions of physical, chemical, and biological stresses on forest ecosystems. The proposed Program will focus on multiple environmental stresses rather than any single one (e.g., acidic deposition, gypsy moth, fusiform rust). The structural basis for the Program is the Forest-Atmosphere Interaction/ Priority Research Program (FAI/PRP), which outlines the scope of Forest Service expertise in addressing questions of interactions between forests and related ecosystems, and the atmospheric environment. The scientific issues addressed by the national PRP are:

1) What processes are involved in atmospheric effects on forests?

2) How do anticipated atmospheric changes influence forest health and productivity?

3) How do forest management practices affect the atmosphere?

The core Forest Service effort described in this Strategic Plan will follow the guidance of the FAI/PRP; however, the broader framework (Figure 1) provides for the needs of other agencies and institutions.

The efforts outlined in Section VI and in the Appendix provide a partial overview of existing and planned research activities. Each will contribute information vital to an understanding of the interactions among air pollution, environmental factors, and ecosystem response in the South. The goal of this plan is to see these programs coordinated through the Forest Service Research Stations in the South. This will help reduce duplication of effort, improve efficiency of expenditures, and maximize regional expertise.

There are a multitude of environmental factors and pollutants that impinge upon the forests of the southern region. How these may affect forests is probably influenced by the goals and management systems utilized by the landowners and these vary with ownerships and subregions or smaller management units. It is not yet known to what degree our limited knowledge ~~Insert Figure 1. Conceptual framework illustrating . . . . .~~ of effects on individual trees can be integrated to apply to specific stands

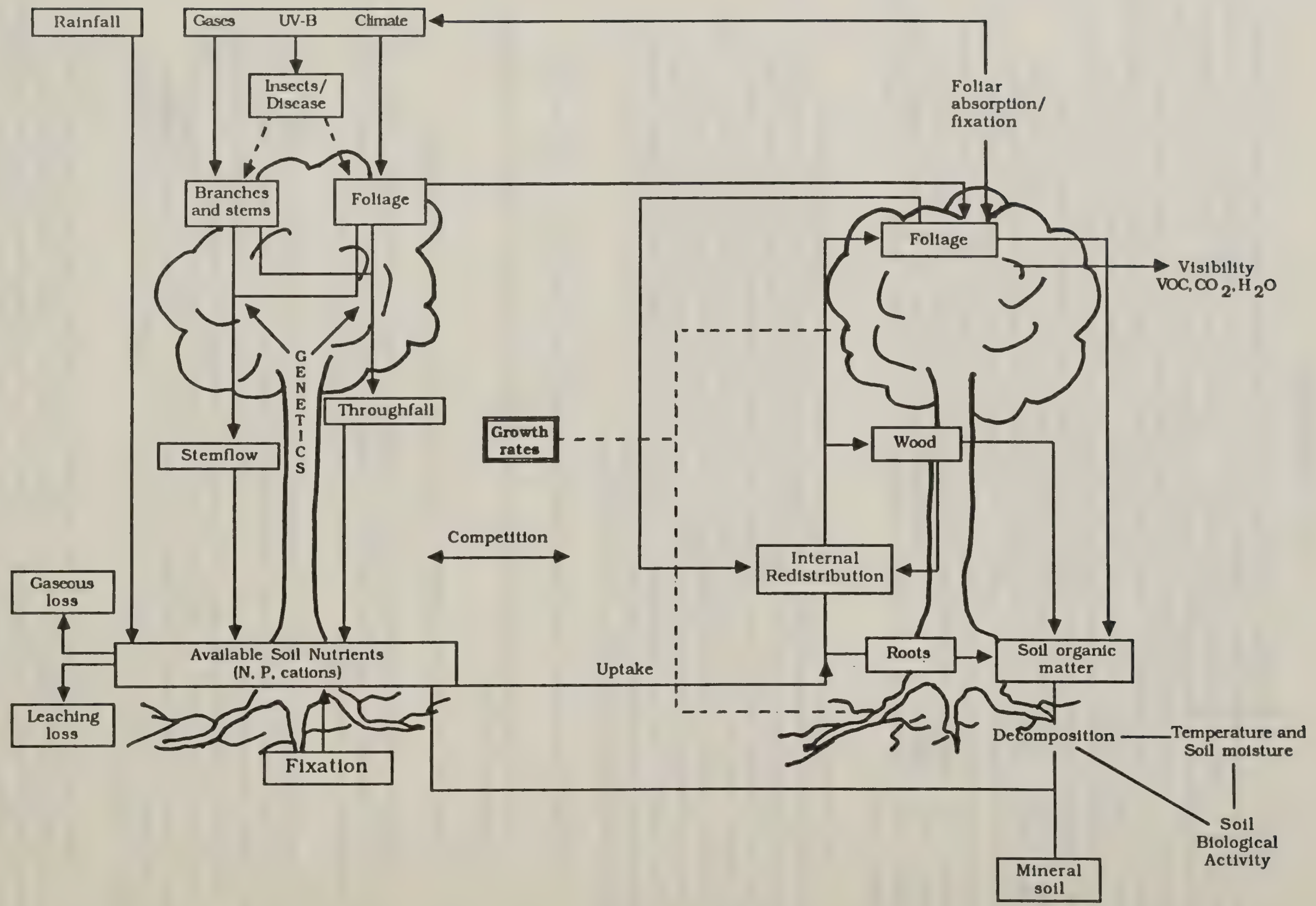

Figure 1. Conceptual framework illustrating the influx, movement and storage of water, nutrients, and carbon within a forest ecosystem. (Adapted from S&I-FRP Annual Report, 1988).

grown under specific silvicultural management systems, and further, to apply to larger blocks of land and ownerships. One of the purposes of this planned research program is to identify research needed to provide the knowledge necessary for making predictions about area-wide effects. A strong Forest Service program, coordinated with various agencies and interest groups identified in the plan, will lead the way in this endeavor.

II. MISSION

The mission is to conduct research and monitoring in the southern region of the United States, to determine the interactive responses among forest ecosystems, atmospheric pollution, and climate change, and to use this knowledge to manage and protect the forest environment and resources.

III. SCOPE OF PROGRAM

A. THE RESOURCE

More than 70 percent of the land in the South is covered by forests; this includes the 40-60% classified as timberland. These forests provide recreation for millions of people, they protect water quality, and provide habitat for diverse wildlife and fish species, in addition to their important role in the economy of the southern region. The states covered by this Plan include: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas and Virginia.

The amount of lumber, plywood, woodpulp, and other wood products qualifies the southern region as one of the Nation's major timber-producing regions. The South's annual harvest is more than 45 percent of the total volume harvested in the United States. Increases in population ensure a growing demand for timber products. In terms of volume, most of the future growth in demand will be for pulpwood and fuelwood. But lumber and plywood demand will increase proportionately. The total demand for timber is projected to rise from 16.7 billion cubic feet in 1984 to 22.3 billion cubic feet by the year 2030 (USDA Forest Service 1988).

Ownership is a major factor in the way timberland is managed in the South. Most of the land, 70 percent, is in private non-industrial ownership. One-fourth of the forests are owned by the timber industry. There are 18 million acres in public lands, about 60% of which is in national forests and the rest is in state forests and wildlife refuges and other State and county lands (USDA Forest Service 1988).

The timberland in the South is composed of many forest types. One-third is pine forest types, with 41 million acres in natural pine stands and 21 million acres in planted stands (USDA Forest Service 1988). Pine species occur in mixtures with hardwoods on 15 percent of the timberland in the South. Hardwoods comprise 50 percent of these stands. Hardwood forests are found on over 50 percent of the South's 93 million acres of forest. Two-thirds of these stands are classified as upland hardwood forests, whose primary species include oaks and hickories, as well as gum, yellow poplar,

black walnut, elm, and maple (USDA Forest Service 1988). The other one-third is classified as bottomland hardwoods. Most bottomland hardwood forests are located in the floodplains of rivers; oaks, gum, and cypress are the most prevalent species but chestnut, willow, and tupelo are found there as well. Currently, several new initiatives to study bottomland hardwoods are underway.

Urban and suburban forests significantly enhance the quality of life in the southern region. More than 30% of the total population in this region is concentrated in cities, where urban and suburban parks and greenways provide recreation and relaxation. Pollution-induced changes in the appearance and vigor of these forests could have significant effects on residential and commercial property value and on the recreational value of parks and greenways.

A unique but important sub-region is the Southern Appalachians, including the mixed hardwood and the spruce-fir forest ecosystems. The latter represents only 62,000 acres in the region; however, its presence in the Great Smoky Mountains National Park, the Blue Ridge Parkway, Mt. Mitchell State Park and in the Pisgah and Jefferson National Forests has ensured high public visibility. Therefore, although not of major economic importance as a timber resource, the aesthetic importance of the boreal, montane forest far outweighs its areal extent.

B. ISSUES

1. Ecosystem Approach

The strategic plan emphasizes the ecosystem as the organizational focus for research (Figure 1). A system approach forces us to consider the biological, chemical and physical features of the environment in an integrated fashion. Linkages among the atmosphere, biota, soils and water quality are necessary to develop this approach. Thus, while tree growth and understanding how trees grow will continue to be a key research area, the ecosystem provides a framework for integrating such seemingly disparate subjects as land use effects on stream quality, pine-hardwood competition under elevated carbon dioxide, and biochemical markers of ultraviolet-B radiation (UV-B) exposure. As more and more forested land is identified for multiple use, the forest ecosystem approach takes on greater importance.

2. Multiple Stresses

Approaching the 21st century, the most critical environmental problem at regional, national, and global scales concerns the effects of man's activities on the atmosphere and, in turn, the impacts of a physically- and chemically-altered atmosphere on human health and on terrestrial and aquatic ecosystems. Currently, at the forefront of this broad topic are questions regarding projected climate changes in response to increasing concentrations of carbon dioxide and other greenhouse gases and elevated levels of UV-B light, consequent impacts on forest productivity and health, and the effects of a variety of atmospheric chemicals on forest ecosystems. Concern regarding the impact of acidic deposition and ozone on our forests is expected to continue beyond the end of current Programs. This is especially true in the South, where only recently have data begun showing significant effects on tree growth and on soil chemistry. Federal land managers who

have been given responsibility for protection of our natural resources are especially concerned about the potential impacts of regional pollutants, for which a specific source cannot be identified.

3. Resource Values

While forest productivity, as it relates to timber production, is an essential aspect of southern forestry, the forests and related ecosystems have many other values. In part of the region, such as the Southern Appalachians, recreation is the fastest growing use of the forest.

Air Quality Related Value (AQRV) is a term used in the Clean Air Act. It is defined as a feature or property of a Class I area that made the area worthy of designation as a wilderness and that would or could be adversely affected by air pollution. AQRVs can be flora, fauna, visibility, odor, cultural resources, soil, water, and geological features or composites of these Class I area features and properties. The Clean Air Act indicated that visibility was an AQRV for most Class I wildernesses.

AQRVs are important because they are part of a process established in the Clean Air Act to prevent significant degradation of air quality in areas where the air quality was better than national standards, while at the same time allowing industrial, commercial, and residential growth. New major sources of air pollution or modifications of existing sources must meet regulations set forth in this process, the Prevention of Significant Deterioration (PSD).

As a Federal Land Manager responsible for Class I wildernesses, the USDA Forest Service becomes involved in the permitting activities for new or modified sources of air pollution that meet criteria under the PSD program. The Federal Land Manager is required under the Clean Air Act to review permit applications and make recommendations to state air regulatory agencies. The basis of the review and subsequent recommendation of approval, denial or modification of a permit is made after an analysis of predicted impacts on AQRVs. If an AQRV is predicted to be adversely impacted by expected emissions from a source, then the Federal Land Manager would recommend that the permit be denied or modified in a way that would lower emissions to levels that would not adversely affect AQRVs.

The approach that the Forest Service Region 8, headquartered in Atlanta and responsible for timber management in the South, is taking in the protection of AQRV is a stepwise progression:

1) AQRVs will be identified using a review of the wilderness legislation, a Forest Interdisciplinary Team and public input.

2) AQRVs will be inventoried to ascertain current conditions.

3) Sensitive indicators will be established for AQRVs and monitored for air pollution related changes.

4) Acceptable levels of protection will be established to gauge changes in the condition of AQRVs.

Forest managers in Region 8 are in the process of identifying AQRVs for Class I wildernesses in the South.

IV. STATE OF KNOWLEDGE

Any new research program must build upon the existing knowledge base if it is to be credible and to use personnel and financial resources wisely. This is especially true in the arena of air pollution and climate change effects on ecosystems, where the available data come from so many different sources, such as Forest Service research, university research, industry studies on growth and yield, and NAPAP funded studies. The following statements are not meant to be all-inclusive of the state of knowledge, but to highlight key issues.

A. CLIMATE CHANGE AND UV-B RADIATION

° Carbon dioxide is increasing globally and temperature is expected to rise as a result, although the magnitude and timing of this change is not known. The impact of this change on rainfall patterns is unclear. One scenario is that, while the average temperature will increase slightly for the next century, it is the amplitudinal shifts in highs and lows that will be the most dramatic.

° Effects of anticipated climate change on most low-elevation southern forests are expected to involve long-term decreases in productivity and changes in species composition (Woodman and Sasser-Furiness 1989). The beneficial effects of increased carbon dioxide concentrations have been shown to be greater for one hardwood species compared to one softwood species (Tolley and Strain 1984a, 1984b).

° It has been well-documented that enhanced UV-B radiation reduces photosynthetic capacity in many herbaceous species (Sisson and Caldwell 1976, Brandle et al. 1977, Teramura 1980, Tevini and Iwanzik 1983, Flint et al. 1985). Kossuth and Biggs (1981) reported a reduced root growth in those species where needle surface area was decreased by UV-B exposure. Effects of UV-B on growth in Pinaceae were observed within five weeks (Sullivan and Teramura 1988, Becwar et al. 1982), and half of the pine species tested exhibited damage under increased levels of UV-B radiation (Sullivan and Teramura, 1988).

B. OZONE AND ACIDIC DEPOSITION

° Regional ozone levels are high (annual 7-hr/day growing season average - 40 to 65 ppb) and often occur at phytotoxic concentrations (60 to 80 ppb) during the growing season (Lefohn and Pinkerton 1988, Reich 1987).

° Ozone has been shown to reduce carbon fixation, affect carbon allocation, and reduce growth for several plant species, including loblolly pine (Reich 1987, Kress et al. 1988, Reinert et al. 1989).

° Ozone is found in concentrations high enough to cause visible injury to trees and other vegetation in the Southeast (U.S. EPA 1986, Garner et al. 1989). Concentrations from 20 to 40 ppb for 8 hours or 90 to 150 ppb for 2 hours have been reported frequently and ozone-induced visible injury on forest trees is well documented (U.S. EPA 1986). There is no evidence that ozone levels are decreasing.

- Trees and other vegetation produce natural hydrocarbons, which are precursors to ozone formation, and may contribute to regional oxidant concentrations (Chameides et al. 1988).

- Sulfur dioxide is rarely found in concentrations sufficient to cause visible injury to vegetation, except in some urban forests in this region (U.S. EPA 1982). Gaseous nitrogen oxides have not been found in concentrations sufficient to cause visible injury to vegetation (National Research Council 1977, Garner et al. 1989).

- Since 1980, direct measurements of the concentrations and deposition of the major constituents of wet deposition are made through the NADP/NTN network (NADP 1985). The pH of rainfall decreases to the West and South. Year-to-year variability in concentration and deposition is relatively small, at least since 1980 (Garner et al. 1989).

- Acidic deposition (sulfur and/or nitrogen) has been shown to change solution chemistry for some soils in the Southern Appalachians (Johnson et al. 1983). Several soil types in the southern United States are expected to respond to sulfur deposition within the next several decades (Binkley et al. 1989, Richter 1989). The impact on long-term soil productivity is not known.

- Similarly, acidic deposition has been shown to alter the chemistry of surface waters draining forested watersheds throughout the Southern Appalachians (e.g., Swank and Waide 1988). Streams draining high-elevation watersheds in this region are beginning to acidify. Long-term impacts and specific regulatory mechanisms remain unclear at present.

- Exposure of seedlings to ozone results in reductions in growth in terms of diameter, height, needle length, needle number, and root growth. Ambient ozone reduced diameter and height up to 22% and 20%, respectively, after two seasons. Foliar biomass reductions were of similar magnitude.

- Photosynthesis in needles of loblolly pine seedlings is reduced by exposure to ozone. Based on studies of the first flush needles, the negative effect of ozone appears due to biochemical rather than stomatal inhibition.

- Acid precipitation effects were significant only for diameter growth in the second year of study. The saplings exposed to the high acid treatment (pH 3.3) grew 12% larger. After one season's exposure there was no apparent effect of the acid inputs on break in dormancy.

- There is some indication that above-ambient levels of ozone decrease carbohydrate concentrations in both secondary needles and in root tissue.

- In 3 of 5 trials with seedlings, the resistance of red spruce to freezing injury was reduced. The effect occurs at the pH of ambient cloudwater (pH 3, 3.5, 4.0), and it is due to sulfuric acid. In one experiment with red spruce saplings, explosure for two seasons to pH 3.3 simulated acid rain caused a transient delay in freezing resistance. In some, but not all ozone exposure experiments, properties related to winter hardiness were altered at ozone

exposures experience in high elevation forests. In two experiments, there was an ozone effect on the degree of winter injury observed in seedlings left to overwinter outdoors.

° Exposure of red spruce seedlings and saplings to ozone and acidified mist for one growing season does not appreciably affect carbon acquisition or allocation patterns. Results from two year's of exposure indicate marginally significant effects on photosynthesis and allocation patterns.

° Branch chamber experiments using mature red spruce at Whiteface Mt., NY showed that ambient levels of airborne chemicals adversely affected foliar pigments, stomatal waxes and cuticle thickness after three months of excluding charcoal reactive gases and ambient cloudwater. In a fortuitous winter injury event, branches from which ambient cloudwater was excluded during the prior summer showed less injury than branches exposed to ambient cloudwater.

° In controlled experiments, red spruce seedlings have been found to be sensitive to dissolved inorganic Al. Concentrations of 200 umol/liter caused reductions in growth, and lower concentrations reduced Ca uptake.

° It is unlikely that acidic deposition has raised labile monomeric Al to levels sufficient to cause spruce mortality through root mortality. Al levels in southern spruce stands approach the 200 umol/l threshold, but in declining stands in the North, Al concentrations are considerably lower.

° There is both field and experimental evidence that Al might be reducing Ca or Mg uptake, but there are no data linking pH, Al, Ca or Mg to tree health in declining stands. Whether or not Al effects on base cation uptake have caused reduced growth is a topic for more research.

° Leaching of cations from spruce crowns is accelerated by exposure to acidic cloudwater. There is evidence from seedling studies that this can affect foliar nutrient status. While there is no clear evidence that this is related to tree health, more research is warranted since foliar analysis suggests a borderline moderate Mg deficiency and available Mg pools in the soil aare very limited at some declining sites.

C. INSECTS AND DISEASE

° The major insects that cause damage to forests in the southern United States are the gypsy moth and the southern pine beetles. The most important diseases are fusiform rust, white pine blister rust, and various root rots (Loomis et al. 1985).

° Climatic factors, especially rainfall and temperature, significantly affect host susceptibility; emphasizing the importance of the potential impacts of climate change.

° Region-wide, southern pine beetle is the most serious insect pest, causing 90% of the mortality to southern pines. While the exact mechanism of susceptibility is unknown, weakened trees are more predisposed to attack. Because of its biological importance,

southern pine beetle is one of the most intensively studied stress factors in southern forestry.

° Nominal, or background herbivory levels constitute one of the main carbon and nutrient cycling pathways in southern broad-leafed forests. Estimates of leaf area removed (LAR) in canopies of hardwoods at Coweeta Hydrologic Laboratory show that, depending upon the tree-defoliator association, insects may routinely convert 10-50% of the green-leaf biomass into highly labile ecosystem components throughout each growing season. Estimates across all watersheds and species suggest long-term LAR ranges from 5-20%. Carbon and nutrients are routed into insect tissue (which is an important resource for forest predators, and its by-products enter the surface litter as carcasses), throughfall and stem flow, altering rates of decomposition, mineralization within the soil, and subsequent plant uptake rates and nutrient loss due to water percolation. Extreme events (insect outbreaks) remove larger amounts of the green-leaf biomass and may significantly affect water quality, principally by increasing NO_3-N in streams (Swank and Waide 1988).

° Annosus root rot is a serious root disease on conifer tree species throughout the southern region. Annual mortality for pine is estimated at 1,433,000 cubic feet. Factors associated with susceptibility to root rot have been extensively studied, and are closely related to soil texture and structure (Meadows et al. 1988).

° Fusiform rust is the most important disease problem in loblolly pine forests today, with estimated annual losses of $35 million (Anderson et al. 1986). Many aspects of rust biology, infection, etc. have been well studied; however, interaction of rust susceptibility with air pollution stress is not known.

D. TEMPERATURE AND WATER STRESS

° The importance of water stress in regulating the growth and development of trees is apparent. Zahner (1962) demonstrated the impact of water supply on height, diameter, and volume growth in loblolly pine. Water deficits result in growth reduction, impact on forest productivity, affect the tree's response to other stresses, and influence species survival and distribution (Teskey and Hinckley 1986).

° Seasonal water deficits occur annually throughout the southern region. Mean annual precipitation is relatively high, ranging from about 1092 mm/yr in the Piedmont of Virginia to about 1651 mm/yr in the Gulf Coastal Plain of southern Louisiana, Mississippi, and Alabama (USDA Forest Service 1969). Most of the region receives between 1140-1400 mm which is well-distributed throughout the year (Van Lear and Douglass 1982). However, potential evapotranspiration in the South is also high, resulting in mean annual water deficits of 25-100 mm throughout the region (USDA Forest Service 1969).

° Leaf growth and development are greatly affected by water deficits (Kozlowski 1968, 1985b). Reduction in cell turgor and subsequent reduction in cell expansion are direct results of water stress. Consequently, most of the decrease in leaf area due to drought is the result of reductions in cell expansion. However, water stress may

also reduce leaf area by accelerating leaf senescence and inducing early abscission (Kozlowski 1968).

° Diameter growth is strongly influenced by water deficits. Zahner (1968) estimated up to 80% of the annual variation in xylem increment of trees in humid regions is due to water deficits. Not as much is known about the effect of water deficits on height growth and shoot elongation.

° Stomata, the primary mediators of gas exchange, are very sensitive to water stress. Photosynthetic rates decline at about the same rate as stomatal conductance. Photosynthesis begins to decline even under mild water stress. As water becomes more limited, as in prolonged drought, the rate of photosynthesis declines rapidly and may even become negligible (Brix 1972, 1979, Teskey et al. 1986).

° Drought may also increase the allocation of carbohydrates to root growth, thus increasing the root:shoot ratio (Teskey and Hinckley 1986).

° Temperature-induced increases in respiration may be a primary mechanism through which temperature controls productivity. Kinerson (1975) found that respiratory losses in loblolly pine accounted for 58% of total carbon fixation.

° The temperature stress associated with forest productivity in the South is heat stress, which results in direct or indirect injury that reduces tree growth. Generally, injury occurs indirectly at temperatures from 15 to 40°C (Kozlowski 1985b). In general, productivity is reduced due to increased maintenance respiration as temperature increases. Net photosynthesis decreases largely due to increased respiration and stomatal closure, as a result of the increased vapor pressure deficit associated with increased temperature. Decreases in net photosynthesis results in reduced growth.

E. NUTRITION

° Mineral nutrition is one of the most important aspects of tree growth and development. A great deal of research has been conducted on the relationship between nutrient deficiencies and physiological processes (e.g., photosynthesis, respiration, nitrogen metabolism, fat metabolism, reproductive processes, and water relations), although primarily on fruit and ornamental trees. Much less research has been performed on forest species (Brix 1971, Lister et al. 1968, DeBell et al. 1984).

° Limitation in rates of nutrient cycling (principally that of nitrogen) is one of the chief factors limiting pine stand productivity in the southeastern United States (Gholz and Fisher 1984). Since rates of nutrient turnover are strongly influenced by climate, changes in climatic regimes will affect nutrient supply.

° Phosphorus and nitrogen are the most commonly deficient nutrient elements in the southern United States (Wells and Allen 1985). The most acute deficiencies of phosphorus occur in the wet, poorly-drained soils of the lower coastal plain, but deficiencies are also

common in soils formed from parent materials low in phosphates (Treshow 1970).

- Potassium deficiency is common in some areas, although, not usually causing severe limitations to forest productivity. Sulfur is frequently deficient (Treshow 1970). And although iron is one of the most commonly deficient macronutrients in forests worldwide (Kramer and Kozlowski 1979), it is not usually growth limiting in the acid soils of the South (Treshow 1970). Deficiencies in boron (Stone et al. 1982) and copper (Treshow 1970) have been reported in areas in this region.

F. GROWTH AND PRODUCTIVITY

- The current forest inventory network (USDA Forest Service-FIA plots and industry timber cruises) is adequate for regional estimates of standing timber. Its suitability for monitoring trends in forest growth related to climate change or other environmental factors is unclear. Initial evaluations of monitoring needs as they relate to statistical and analytical methods and to data collection procedures neither rule out nor establish the specific role of the forest inventory network in future monitoring activities.

- Sheffield et al. (1985) presented evidence of growth reductions in terms of three different measures of growth rates. Actual volume of net annual growth declined over extensive areas of the Southeast. Average annual radial growth rates of individual trees also declined. Finally, basal area per acre appears to have decreased more than can be accounted for by changes in stand density and age.

- The most extensive assessment made using randomly-located plots shows that the percentage of red spruce which were dead in the Southeast 1987-88 was very low and well within the range considered normal. The percentage of spruce which were dead in 1987-88 was less than for Fraser fir or for other species. Overall, red spruce condition is excellent. If there is unusual mortality, it is localized. Fraser fir mortality over the past three decades has been extremely heavy and has been caused by the balsam wooly adelgid.

- Red spruce radial growth at very high elevations decreased after about 1970. The reasons are unclear, but climate does not appear to play a major role.

V. RESEARCH NEEDS

The previous section identified areas where knowledge has been gained relative to environmental stress factors and tree or forest ecosystem response to that stress. However, while some of these areas have a long history of research, studies dealing with air pollution impacts are fairly recent (e.g., Forest Response Program) and knowledge gaps are substantial. The greatest challenges will be to scale-up our findings from the individual plant, seedling or tree, to the stand level and to evaluate effects on forest ecosystems. Ultimately, we must be able to integrate and predict at the system level to make management decisions, whether on timber production, wilderness protection, or multi-use and sustained yield.

The FAI/PRP of the USDA Forest Service has identified 4 areas within which all research elements can be incorporated: (1) effects of the atmosphere on ecosystems, (2) effects of ecosystem change on the atmosphere, (3) assessment of long-term changes, and (4) prediction of ecosystem response. This document will use the same categories as a means of organization.

The research needs described below fall into two broad areas of approach: (1) repeated measurement or monitoring of field characteristics, and (2) elucidating mechanisms of response, both at the plant, stand and system levels. (Figure 1 provides a framework.) As the research efforts are pursued, the following general needs identify the guiding strategy for research:

- Seedling vs tree response characteristics to different stresses;
- Tree vs stand response under variable stress;
- Modeling within and between these components;
- Evaluation of system development and <u>interactive</u> process-level models;
- Understanding effects on all stages of development or organization (i.e., seedling/tree/stand); and
- Understanding genetic tolerance to the different stresses.

Each research need must be approached at multiple levels of investigation. For example, in understanding the response of southern pines to acidic precipitation and ozone, the Southern Commercial Forest Research Cooperative (SCFRC) has been better able to achieve its objectives by using a combination of experimentation in the greenhouse and the field, and through in-situ field measurements.

All research areas are considered to be important by the scientific community in the South; however some prioritization is necessary in order to efficiently distribute resources. Each sub-area has several projects which are ranked by Priority I, II or III (highest to lowest). Criteria considered in the ranking included: (1) capability within the region to conduct the research, (2) turnaround time of findings, (3) degree of visibility and client concern, and (4) potential advancement of science.

A. EFFECTS OF THE ATMOSPHERE ON ECOSYSTEMS

1. <u>Forest Response to a Changing Physical Environment</u>

The physical climate system, namely the interactions of solar radiation, UV-B, atmospheric dynamics, and the hydrologic cycle, is coupled with biogeochemical cycles of nutrients. These factors directly influence the functioning of ecosystems. As the concentration of carbon dioxide and other greenhouse gases increases in the atmosphere, temperature is expected to increase. Rainfall and other precipitation patterns will change, but the magnitude and direction of change is unclear. Any change in rainfall and temperature patterns is also likely to alter fire frequency in the region, an ongoing issue in any forested environment. From a system standpoint, these changes are certain to impact, to some degree, the structure and composition of the forest ecosystem, but there are numerous uncertainties. It is likely that the greatest effect will be seen in ecosystems at the edge of their range, for example, the high-elevation spruce-fir forests in the Southern Appalachians. Land managers must be able to predict potential loss

of species, or changes in plant or animal communities, due to environmental impacts.

The temperature of the air and the soil, the availability of moisture, and UV radiation are all known to affect the physiological processes of plants. The effects of these changes on carbon fixation and allocation, biomass production, VOC production, water-use efficiency and a host of other physiological processes need to be quantified for tropical forest species, southern pines, hardwoods, and other plant types, before we can predict the effects of climate change on forest productivity and composition.

Acute and/or chronic alterations in the above-ground atmosphere can potentially alter root properties indirectly through the foliage by shifting carbon allocation, or directly via precipitation inputs into the soil. The importance of the above- and below-ground processes in the control of plant growth both for woody and herbaceous species must be delineated under natural conditions, whereas a better understanding of mechanisms of effect is more readily accomplished under controlled conditions. Special emphasis will be placed on the evaluation of the linkages between physiology and growth processes, to include above- and below-ground plant growth and development. While the focus of the research is on the biological processes, this work will not be able to be done without concomitant air quality and meteorological data.

Priority I

a) Identify effects of climate change and UV-B on carbon fixation, allocation, and growth, above- and below-ground. This includes controls on leaf area and the general topic of leaf area dynamics.

b) Identify effects of climate change and UV-B on water and nutrient balance within plants, above- and below-ground.

c) Evaluate alteration of streamflow amount and timing from forested watersheds due to climate variability.

Priority II

a) Describe the genotype and genotype X environment interaction of response (i.e., genotype sensitivity).

b) Develop, through testing and breeding, tolerant species and families to use on high stress sites.

Priority III

a) Characterize landscape patterns of water stress/availability.

2. Forest Response to a Changing Chemical Environment

Changes in acidic deposition, ozone and other gaseous pollutants, may alter ecosystem nutrient cycling and nutrient retention by changing supply or by affecting processes. The deposition of sulfur and nitrogen to forested ecosystems in the South has increased with industrialization, resulting in significant changes in nutrient fluxes in some locations (e.g., Coweeta Experimental Forest, Great Smokies National Park). Changes in soil characteristics and precipitation chemistry have been observed to influence

the morphology and size of the root system of a tree, presumably altering nutrient and water transport within that tree.

Cycles of sulfur, nitrogen, and nutrient cations, and the mobility of elements such as aluminum, can be influenced by atmospheric deposition. Specific effects vary by soil types; effects may be event-related or occur over longer time periods. For example, much of the forested area of the Southeast is located on old, weathered soils (Ultisols) having few primary minerals and low base saturation. Research within the SCFRC and from the EPRI-Integrated Forest Study has pointed to changing soil solution chemistry at ambient deposition levels. The critical role of sulfate adsorption in consuming protons and how sulfate desorption progresses under changing sulfate inputs requires further study. Similarly, little is known about the long-term effects of atmospheric itrogen deposition to ecosystems, whether nitrogen is limiting or, as is common in much of the South, phosphorus is deficient.

Priority I

a) Identify mechanisms of the effects of atmospheric inputs on nutrient cycling in target ecosystems.

b) Identify effects of ozone, carbon dioxide and acid deposition on carbon fixation, allocation and growth, above- and below-ground.

c) Determine mechanisms of ozone uptake and adsorption and the subsequent impact.

d) Describe relationships between changing deposition, site chemistry, and plant nutritional response.

e) Evaluate effects on site quality and litter decomposition.

Priority II

a) Determine extent of soils potentially sensitive to acidic deposition.

b) Determine effects on microbial regulation of nitrogen, sulfur and phosphorus transformations.

Priority III

a) Evaluate effects of changes in chemical constituents in the atmosphere on nutritional value of plants for wildlife.

b) Determine mechanisms of water utilization efficiency under pollutant impact, especially carbon dioxide and ozone.

3. Interactive Stress

There are many natural environmental stresses which are known to affect forest composition and productivity (see Section IV). Several of these are of particular interest to this program due to their potential interactions with climate change, ozone and other pollutants: (1) insects and diseases, (2) competition, and (3) water stress. Regarding insect and disease interactions, the Forest Response Program identified this area of research

as an important issue; however, only with regard to eastern hardwoods was it of sufficient priority to initiate research PRIOR to establishing a linkage between tree response and air pollution. After 3 to 5 years of research in southern pine, spruce-fir, and hardwood forests, the role of air pollution and other environmental stresses in predisposing forest stands to attacks by insects and disease has increased in priority. Forest industry, in particular, has focused on this area with regard to climate change questions.

Changes in insect and disease incidences may be the first response of forest ecosystems to climate change. It is essential that the research program develop means to predict the type and severity of insect and disease response. In light of the substantial knowledge base for fusiform rust, southern pine beetle, and other major pests, it is appropriate that investigations of the links between these pests and stress be undertaken. (NOTE: While several organisms are mentioned specifically in the research areas listed below, it is not the Plan's intention to exclude other organisms. The authors recognize the importance of gypsy moth, tip moth, pitch canker and Dogwood anthracnose, and others too numerous to mention, in the structure and productivity of southern forests.)

Research has illustrated that variation in response to environmental stress can be extremely large among different plant species. As such, to the extent that the different genera in a forest ecosystem respond differently to the same environment, changes may accelerate or decrease the growth rate of one plant constituent relative to other plant species within the ecosystem matrix, and may result in shifts in species composition. This has occurred in forests of the San Bernardino mountains due to air pollution from the Los Angeles basin.

Priority I

a) Determine interaction between fusiform rust, and ozone and carbon dioxide on pine productivity.

b) Determine interaction between southern pine beetle and hardwood defoliators, and ozone/carbon dioxide impact on tree productivity.

c) Describe the effects of water stress on the control of plant response to ozone and carbon dioxide with and without insect and disease interactions.

Priority II

a) Evaluate changes in rust disease dynamics under alterations in climate (i.e., changes in water and temperature regimes).

b) Evaluate spatial patterns of major insect and disease species in the South under elevated ozone (greater that 50 ppb-7 hr average) and changing climate.

Priority III

a) Identify mechanisms of inter- and intraspecific interactions, above- and below-ground, considering trees, shrubs and herbaceous species.

b) Determine interaction between "root rots" and ozone.

c) Identify or develop control strategies to ameliorate the problem.

B. EFFECTS OF ECOSYSTEM CHANGE ON THE ATMOSPHERE

1. Biogenic Emission of Gases

While the impact of the atmosphere on ecosystems typically has been a primary focus of research, ecosystem processes are known to alter certain atmospheric components. Recent evidence has shown that natural hydrocarbons emitted by trees and other vegetation are significant ozone precursors. Other gases with major biological sources are nitrous oxide, hydrogen sulfide and methane. It has been hypothesized that as plants are subjected to drought stress, hydrocarbon emissions will increase. This and other processes must be considered as the interactions between climate change, ozone and ecosystem response are evaluated.

Priority I

a) Determine the magnitude of speciated hydrocarbon emissions from major forest species and forest types.

b) Determine the magnitude of biogenic emissions of isoprene, pinenes, methane, etc. from forest systems including soils.

c) Evaluate seasonal effects on speciated hydrocarbon production.

Priority II

a) Determine the influence of stand composition, and physical and chemical changes (e.g., water stress and pollutant stress) on hydrocarbon and other biogenic emission rates from natural and managed forests.

b) Identify the extent to which the emission ratios for various hydrocarbons and other biogenic gases are correlated with particular environmental stresses on forest trees.

c) Evaluate the impact of hydrocarbons and other atmospheric gases of biogenic origin on the levels of ozone and other secondary pollutant gases in urban and non-urban regions of the South.

d) Determine activity of biogenic gases in atmospheric processes, especially those leading to ozone formation or depletion.

Priority III

a) Identify the mechanisms by which hydrocarbons produced by trees are released into the atmosphere.

2. Land Management Influences on the Atmosphere

Landform and vegetative cover are two important factors which influence local and regional climate. While the effects of land use changes on water budgets, economics, etc. have been documented, little work has been done to understand how land management affects gaseous or particulate emissions, site humidity and carbon fixation. It is likely that trace gas and

particulate emissions associated with biomass combustion during wildfires, forest clearing, and forest management operations may play a role in climate change scenarios. Management of tropical forests may prove to be the most important area for study, although forest operations in temperate areas cannot be ignored.

Priority I

a) Determine how wildfires, harvesting, and other management practices (including fire) influence forest/atmosphere interactions.

b) Evaluate effects of site conversion (e.g., agriculture to pine plantations) on biogenic emissions.

Priority II

a) Evaluate effects of intensive forest management practices on long-term soil stability and nutrient cycling, as might affect future sensitivity of soil systems to atmospheric deposition.

C. ASSESSMENT OF LONG-TERM CHANGES: ECOSYSTEM MONITORING

Cycles of unusually wet or dry years demonstrably influence the vigor and growth of individual trees. On a longer term, the growth and composition of entire stands can be modified by climate cycles. However, the interaction between timing and duration of extreme climatic conditions; tree reproduction, growth and mortality; and stand dynamics and successional processes is not adequately described for many southern forests. Less is known about the spatial and temporal patterns of forest conditions under elevated ozone concentrations, or sulfur and nitrogen deposition. For example, the absence of long-term data on soil chemistry has significantly hampered our ability to evaluate the impact of acidic deposition on ecosystems. Short-term (less than 5 years) experimentation is not an adequate substitute for these databases.

Naturally regenerated pine stands represent roughly two-thirds of the pine acreage in the Southeast. Forest Inventory and Analysis (FIA) data show a large decline in recent basal area growth rates of these stands. A major difference in stand condition between the more recent survey and past surveys is the greater amount of non-pine plant components now present. To understand the behavior of pine growth at a process level we must be able to quantify the roles of other major plant constituents, both in natural stands and in plantations.

The National Vegetation Survey of the Forest Response Program has developed monitoring/survey research and implementation strategies over the past four years. Monitoring here is defined as the long-term periodic measurement of selected physical and biological parameters in order to establish baselines and to detect and quantify change over time. The experience gained during the FRP allows us to research, develop and implement appropriate forest monitoring. **The overall objective will be to "determine long-term trends in forest condition."** Emphasis will be on the initiation of necessary research studies to accelerate the collection of appropriate baseline data needed for the design of monitoring systems and the analysis of monitoring information. A balance will be struck between intensive, frequent monitoring at a few sites and the extensive "survey" approach.

Priority I

a) Design and implement a long-term monitoring program to evaluate status and trends in the condition of forest ecosystems, in relation to a changing forest environment.

b) Identify and monitor sensitive bioindicators of climate change and pollutant impact (emphasis will be placed on AQRVs).

c) Establish and continue a system of air-quality monitoring sites relevant to southern forest ecosystems: carbon dioxide, ozone, UV-B, wet and dry deposition, and meteorology.

Priority II

a) Evaluate the use of remote-sensing technologies for detection of ecosystem response to physical and chemical climate change.

b) Develop techniques and approaches for interfacing atmospheric processes (and models) and ecosystem processes (and models).

c) Determine long-term trends in the amount and chemistry of stream flow from forested watersheds, in relation to physical and chemical changes in the atmospheric environment.

Priority III

a) Determine those factors which control the formation of oxidants in forested regions.

b) Provide for better characterization of solar radiation at all field research locations, specifically for use in water balance research and modeling of carbon fixation/allocation in plants.

D. PREDICTION OF ECOSYSTEM RESPONSE: ECOSYSTEM MODELING

Evaluating potential changes within forest ecosystems requires models that integrate individual plant responses into stand- and community-level responses. Such models will be used to pose "what if" questions regarding changes in the atmosphere, changes in water and nutrient availability, changes in forest structure and composition, and changes in plant growth. Emphasis should be placed on process-based models so that potential impacts of changes in the physical, chemical, and biological environment on tree growth and stand dynamics can be evaluated. A key objective of the modeling is to evaluate the relationship between forest structure and productivity, and water quality, under a changing climate. (This research element is analogous to the Quantitative Studies area of emphasis within the Southern Forest Productivity Program.)

Priority I

a) Initiate modeling to guide research activities and integrate information collected within this Strategic Plan.

b) Modify and improve hydrologic models for predicting water balance and streamflow in response to climate change.

c) Develop/refine process-based stand dynamics models for southern forests: tropical, southern pine, and hardwood.

d) Develop/refine current, empirical growth and yield models to incorporate atmospheric changes and silvicultural practices, for pines and hardwood stands.

Priority II

a) Develop techniques and approaches for interfacing ecosystem models at different spatial and temporal scales.

b) Develop integrated ecosystem model(s) of hydrology, productivity and biogeochemistry.

Priority III

a) Develop methods for linking forest damage models with economic models.

VI. RESEARCH CAPABILITIES

Many of these priority research and monitoring needs have been identified as components of future programs (Figure 2). Many are being investigated under existing programs outside the context of air pollution and climate change. The goal of this Strategic Plan for Southern Ecosystem Health and Productivity in a Changing Environment is to integrate existing and planned activities, thereby optimizing information flow for policy decisions and encouraging participation where expertise can be maximized. An important aspect of implementing this strategy is to provide a means for continuing use of the facilities and the intellectual "critical mass" established under the Forest Response Program. Involvement in NAPAP has shown that multi-agency/institutional, multi-objective programs are the most efficient means of addressing complex environmental issues.

This section gives a short overview of existing programs and research activities which are studying pollution impacts in the southern region. The Appendix contains a more complete overview of both existing and planned research which contributed to the development of this Plan. The opportunity to coordinate these efforts, and the need to develop well-defined goals to minimize redundancies is apparent.

A. FOREST RESPONSE PROGRAM

The Forest Response Program (FRP) is a research program designed to evaluate the responses of forests to acid deposition and its associated pollutants. It is sponsored by the National Acid Precipitation Assessment Program (NAPAP) and is funded by the U.S. Environmental Protection Agency, USDA Forest Service, and the National Council of the Paper Industry for Air and Stream Improvement (NCASI). According to a congressional mandate given to NAPAP, research in the FRP is to include efforts aimed at: (1) defining areas of impact and the identification of sensitive areas and areas at risk; (2) developing dose-response functions with respect to soils, soil organisms, and forest tree species; and (3) establishing and carrying out

Figure 2. Current or Planned Research and Monitoring Activities South-wide.

	Effects on Ecosystems			Effects on Atmosphere		Ecosystem Monitoring	Ecosystem Modeling
	Physical	Chemical	Interaction	Biogenic Emission of Gases	Land Management Effects		
USDA Forest Service							
SO		X	X	X	X	X	X
SE	X	X	X	X	X	X	X
R8			X			X	
EPA							
Global Climate							X
EMAP			X			X	X
Nat. Trop. Ozone		X					X
UV-B	X			X			X
(Stratospheric Ozone)							X
Air Monitoring				X		X	X
(including hydrocarbons)							
DOE							
Biomass/CO2		X			X		X
FOREST INDUSTRY	X	X	X				
TREE IMPROVEMENT COOPS	X	X			X		X
EPRI		X	X			X	X
NCASI		X					X
Southern Oxidants Study		X		X			X
NPS		X			X	X	
USDA-ARS	X		X				X
NSF	X	X					X
SURA						X	

system studies with respect to tree physiology, soil chemistry, soil microbiology, and forest ecosystems.

Representatives of the EPA, the Forest Service, and NCASI, using the NAPAP mandate, developed three broad policy questions that provide the basis for the FRP research strategy:

1) Is there a significant problem of forest damage in the United States which might be caused by acidic deposition, alone or in combination with other pollutants?

2) What is the causal relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in the United States?

3) What is the dose/response relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in the United States?

A number of agency and institutional research activities are currently ongoing in the South. Figure 3 shows the location of this work and a brief description of the scope of the research is provided below.

Research in the FRP is organized by major forest region to help focus on specific sets of questions, problems, and symptoms that are associated with a particular forest region. Research Cooperatives have been set up for four major forest regions of concern.

Several projects focusing on the response of southern pines to air pollutants were initiated by the Southern Commercial Forest Research Cooperative (SCFRC) of the Forest Response Program of NAPAP. These studies serve as the core research effort for the Southern Ecosystem Health and Productivity plan, due to the expertise developed at the locations, and the ongoing institutional support. These efforts may form the core for future research programs; however, there are additional capabilities in other locations throughout the region that can contribute in the future, and it is not the intention of the Plan to be restricted only to existing projects. More details on these and other planned Programs are described in the Appendix.

1. Southern Commercial Forest Research Cooperative

The Southern Commercial Forest Research Cooperative (SCFRC) is evaluating the effects of pollution on southern pine species of commercial importance. Highest priority has been placed by the SCFRC on questions about hypothesized mechanisms involving tree physiological processes directly related to growth. Secondary in importance are questions about mechanisms having an indirect impact through soils and soil microorganisms. Of lowest priority for the southern commercial forests is the question involving nitrogen deposition and winter injury. (This question is more relevant to high elevation mountain forests and northern latitudes where severe winter conditions are frequent). Prioritization of research emphasis was based upon evaluation of the state of knowledge through the literature and conclusions about the probability of the individual mechanism having a significant impact on forest productivity in this region.

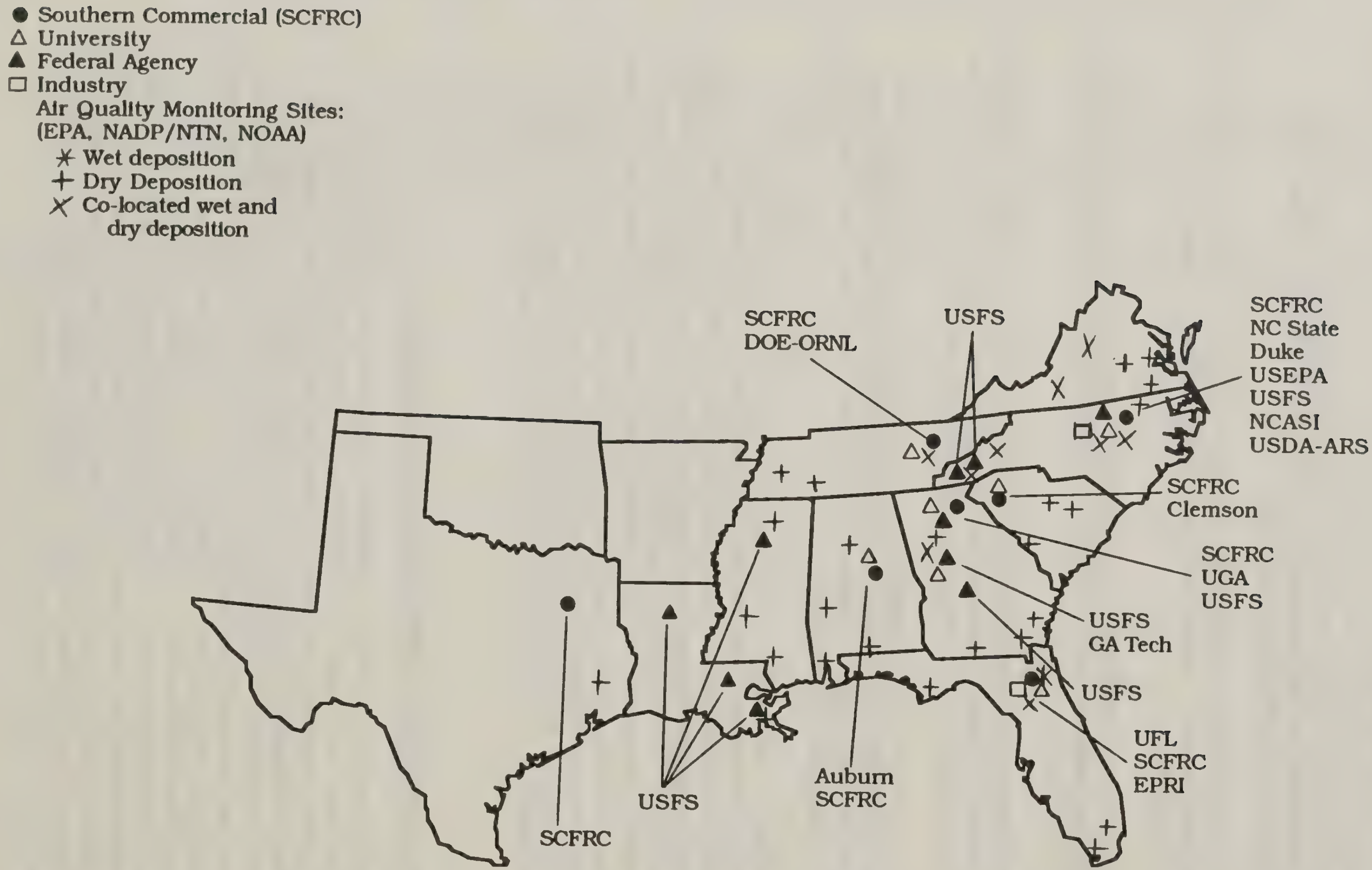

Figure 3. Location of ongoing research on natural or anthropogenic stress effects on forests in the South.

The SCFRC research strategy combines the elements of short-term, more extensive studies and longer-term, more intensive studies. In order to obtain information on the response of many different families of loblolly pine, several short-term laboratory and greenhouse studies were undertaken. Laboratory and greenhouse studies such as those at North Carolina State University, Oak Ridge National Laboratory, and Texas A&M University, and those that are being conducted at the Center for Forest Environmental Studies in Macon, Georgia, allow the evaluation of a larger number of species (and/or genotypes) in a relatively short period of time. Although laboratory results indicating effects of air pollution on seedling growth or physiology may not necessarily indicate that trees in forest environments would be affected in the same way, because of age-related physiological differences, as well as environmental differences (e.g., soils, climate), laboratory studies can provide insight into possible responses in the field. The SCFRC is also supporting uncontrolled field studies on one of EPRI's Integrated Forest Study sites (See page 24).

To maximize the usefulness of the information obtained from field studies, the SCFRC is employing the multi-site concept of Intensive Research Sites. These are coordinated field studies providing a detailed examination of the response of pine seedlings and saplings to acid precipitation and ozone at five different locations across the South. The five sites were selected to reflect the regional distribution of southern pines, and emphasize the three most important commercial species. The establishment of these Intensive Research Sites is a key component to the SCFRC research strategy. These sites provide information to aid in the development of a regional assessment and will permit better interpretation of results because they employ an integrated approach to understanding the effects of airborne chemicals.

Pollutant concentrations are being manipulated by the use of open-top exposure chambers with rain exclusion covers and a rain distribution system for applying simulated rain. The five sites follow common protocols and use similar experimental designs. The sites also use the same rain acidities and chemical constituents. The research includes intensive measurements of plant response and monitoring of the environment (inside and outside the chambers). Exposure-response, tree physiology, and soil nutrient availability studies are being conducted at these locations.

In the future, these sites could be used for further investigations of the effects of ozone and acidic precipitation on southern forest species. The SCFRC core studies are only the first step in understanding the complex relationships between air pollutants, environment, genetics, competition, and tree response. The sites could be used to examine the effects of air pollutants with other environmental factors, such as drought, warming, elevated carbon dioxide, increased UV-B, insects, or disease.

Critical literature reviews augment the experimental work at the different locations. One review focused on the impact of both natural and anthropogenic stress on southern forests; another assessed the relative importance of acidic deposition, ozone and other nitrogen- and sulfur-derived pollutants on forests in eastern North America; and the third literature review addressed impacts of nitrogen deposition on mycorrhizal populations.

2. Atmospheric Exposure Cooperative

The Atmospheric Exposure Cooperative (AEC) has an important role in the Forest Response Program. Begun in 1985, its major purpose is to provide reliable information on the exposure of forests to airborne chemicals. This is carried out in two ways: (1) across the region, based on data collected by other organizations, and (2) in the vicinity of intensive research sites, based on new measurements made specifically to monitor ambient air quality at various locations within the region. The airborne chemicals of interest include gaseous sulfur dioxide, nitrogen dioxide, nitrogen oxide, ozone and other photochemical oxidants; major cations (hydrogen, potassium, calcium, magnesium, and ammonium) and anions (sulfate, nitrate, phosphate, chloride) in precipitation; total biologically-available N compounds (ammonia, nitric acid vapor), toxic elements (lead, cadmium, fluorine), and biologically-active organic substances.

The AEC provides vital information and is a key link for all of the cooperatives of the Forest Response Program. It is managed by the EPA in Research Triangle Park, NC. The SCFRC has worked closely with the Atmospheric Exposure group during its development and will continue to do so in the future to ensure air quality data are available in non-urban locations.

3. National Vegetation Survey

The National Vegetation Survey (NVS) provides the FRP with estimates of the area of forests showing unexplained foliar symptoms of stress or unexplained reductions in growth. A well-defined linkage exists between the SCFRC and the NVS programs. The benefits of such participation are many. Research results from the SCFRC will assist in the development and execution of the surveys by identifying the appropriate measurements to be made in field plots and at the forest health monitoring sites. In addition, the experience and knowledge of the scientists working within the SCFRC will be helpful in the proper interpretation and analysis of data obtained by the NVS. The NVS assists the work of the SCFRC by (1) providing population level estimates of the magnitude and extent of the resource in question along with an early indication of visible symptoms of damage and reductions in growth, (2) providing a database of forest resource information to assist in the analysis of site studies and the application of site studies to general tree populations, (3) assisting in the characterization of research sites, and (4) developing a long-term forest health monitoring program.

4. Spruce-Fir Research Cooperative

Research began in 1985 on the causes and effects of air pollutants and acid deposition on spruce-fir forests of the northeastern and southeastern United States. The Spruce-Fir Research Cooperative (SFRC) addresses two primary questions: (1) Why are spruce showing visible symptoms of damage, reduced growth, and increased mortality? and (2) What are the effects of air pollutants and acid deposition, if any, on spruce-fir forests throughout their range? Scientists are testing various hypotheses, including those involving natural stresses such as competition, drought, frost, biotic pathogens, in addition to nutrient deficiencies, and foliar fertilization from the atmosphere, deposition of acidic substances, gaseous pollutant exposure, and trace metal deposition and/or accumulation. The SFRC conducts

both mechanistic and ecosystem monitoring studies in the South, specifically in the higher elevations of the Southern Appalachians of Tennessee, North Carolina, and Virginia.

B. ELECTRIC POWER RESEARCH INSTITUTE

1. Integrated Forest Study

The Integrated Forest Study on the Effects of Atmospheric Deposition (IFS) is a 5-year, multi-site program funded by the Electric Power Research Institute and directed by scientists at the Oak Ridge National Laboratory. The principal objective of the IFS is to determine the effects of atmospheric deposition of sulfur, nitrogen, and other atmospheric compounds on forest nutrient cycling. The study integrates (1) field measurements of atmospheric deposition and nutrient cycling in a variety of forest sites, (2) experimental research, including laboratory and field studies, to investigate selected atmospheric and soil processes in greater detail, and (3) model development to address these issues.

The research is being conducted at 17 forested sites in the northwestern, northeastern, and southeastern United States and in Canada and Norway. These sites represent a range of conditions in terms of climate, air quality, soils, and vegetation, which will facilitate the testing of hypotheses regarding the effects of atmospheric deposition on forest nutrient cycles. Nine of the IFS sites are located at both high and low elevation forests in the Southeast: loblolly pine stands in Oak Ridge, Tennessee, Durham, North Carolina, and Clarke County, Georgia; slash pine in Gainesville, FL; white pine and mixed hardwoods at the Coweeta Hydrological Laboratory; and spruce and beech in the Great Smoky Mountains National Park. The site in Gainesville is part of the Southern Commercial Forest Research Cooperative, while sites near the IFS forests in the Smoky Mountains are part of the Spruce/Fir Research Cooperative. Responsibility for site operation throughout the IFS is in the hands of the principal investigators at each site.

At the 13 IFS forests designated as intensive deposition measurement sites (6 of which are in the Southeast), detailed data on atmospheric chemistry, wet deposition, and meteorology are collected continuously (meteorology) and on an event basis (atmospheric chemistry and wet deposition) throughout the year. All measurements are taken at or adjacent to the study plot used for collection of nutrient cycling data. These data include ion fluxes in throughfall, stemflow, and soil water; vegetation structure, ion pools, and dynamics; and detailed studies of soil chemical characteristics and weathering rates. Data collection began in 1986 and will continue into 1989. Data from the IFS are being used to develop a model of deposition interactions with forest nutrient cycles for the purpose of predicting the effects of various deposition scenarios. A book synthesizing the results of all field and experimental work in the IFS is being prepared for publication in 1990.

2. Response of Plants to Interacting Stresses

The objective of the Electric Power Research Institute's (EPRI) ROPIS program is to address the role of air pollution in governing the productivity of forest trees in the United States, and it is designed to

complement EPRI's Integrated Forest Study. The principal hypothesis of ROPIS is that the responsiveness of forest vegetation to wet and dry deposited pollutants is appropriately evaluated in the context of multiple stresses of anthropogenic and natural (e.g., drought, nutrition) origin. Given the complexity in space and time of these interacting stresses, the ROPIS program combines multiple-year experimental studies with process-level models to develop an understanding of how air pollutants may influence forest trees.

The ROPIS-SOUTH project addresses the role of rainfall chemistry, soil magnesium status, and ozone on loblolly pine and is being conducted at Oak Ridge National Laboratory's (ORNL) field research facility. The project is cofunded by EPRI and the Tennessee Valley Authority (TVA) and was initiated in 1986. This multiple-year field project ends in 1989, and several open literature publications document initial and ongoing results. Beyond the individual publications, a synthesis manuscript is planned.

C. USDA FOREST SERVICE

The research branch of the Forest Service is conducting studies on the effects of air pollution on forest health. In Coweeta, North Carolina, both long-term monitoring on permanent plots and short-term process-level studies of deposition impacts on tree physiology are on-going. In Athens, Georgia, tree root dynamics under natural and man-made stresses are being studied.

The Southern Station's Institute of Quantitative Studies in New Orleans, Louisiana, has developed statistical methods for tree-ring analysis and coordinated large projects on southern pine plantation growth trends, and is helping devise monitoring systems. The Station's Institute of Tropical Forestry, Rio Piedras, Puerto Rico, conducts research on nutrient and carbon cycling, and related studies emphasizing tropical forests. Other Southern Station units conduct work on tree seed, long-term growth and yield and genetics, and watershed aspects of air pollution impacts.

The USFS Region 8 is performing surveys to detect, evaluate and monitor air pollution effects on resource values. These surveys are performed on temporary and permanent plots.

D. NATIONAL ATMOSPHERIC DEPOSITION PROGRAM/NATIONAL TRENDS NETWORK

In 1978, in response to the growing awareness of the need for information on the chemical climate, and in particular, the chemistry of rainfall in the United States, the National Atmospheric Deposition Program (NADP) was established by the Association of State Agricultural Experiment Stations. It was developed to conduct research, in cooperation with federal, state and private research agencies, on atmospheric deposition. In 1978 the NADP established a national monitoring network to collect weekly data on precipitation chemistry. In 1982, the NADP became responsible for coordinating the operation of the National Trends Network of the National Acid Precipitation Assessment Program, and the two monitoring networks were merged (National Atmospheric Deposition Program 1987).

The National Atmospheric Deposition Program/National Trends Network (NADP/NTN) is designed to identify spatial and temporal trends in precipitation chemistry in the United States. The NADP/NTN network encompasses 204 stations, located in 47 states and including sites in Puerto

Rico and American Samoa. There are sites in every state except Connecticut, Delaware, and Rhode Island (National Atmospheric Deposition Program 1987).

The NADP/NTN monitoring program is characterized by uniform data collection criteria and protocols for siting, sampling methodology, analytical procedures, data handling, and overall network operation (National Atmospheric Deposition Program 1987).

E. NATIONAL MONITORING NETWORK

The objective of the National Monitoring Network (NMN) is to determine the levels and geographic distribution of atmospheric pollutants. From this information, scientists are determining trends in the deposition and concentration of pollutants in order to begin answering important questions about the relationship between atmospheric pollution and ecological changes. Trends analysis will provide answers to such questions as: Are overall deposition rates increasing, decreasing, or remaining stable? The resulting conclusions will provide a strong base for assessing the effectiveness of control devices being used to reduce pollutant emissions from sources such as coal-fired power plants, automobiles and industrial activities. Information on deposition amounts and trends will enable researchers to determine how deposition of atmospheric pollutants may affect lakes and streams, forests, crops, building materials and possibly human health.

The NMN monitoring sites are chosen to represent the exposure levels experienced by the surrounding regions, and influence by nearby point sources of pollution should be minimal. Thus, guidelines are followed for locating sites at or beyond minimum distances from pollution sources such as urban areas, power plants, factories and roadways and to reduce obstructions from trees and buildings. The NMN has a dense network of sites in the eastern United States, enabling the determination of spatial and temporal deposition trends. The EPA plans to expand the network's spatial coverage by adding 15 more sites to the 60 existing sites.

The flexibility and widespread deployment of the NMN provides EPA with the ability to respond quickly and effectively to the needs created by emerging environmental issues. The NMN's adaptability will enable EPA to develop additional activities to address recently identified environmental issues or to use the network as an "early-warning system" for detecting the presence of new environmental contaminants. The recent concern about the protective ozone layer is an example: Are levels of harmful UV radiation increasing because of decreasing levels of stratospheric ozone? The NMN is helping to answer this question through deployment of monitoring equipment to measure UV radiation levels.

F. DEPARTMENT OF ENERGY

The Department of Energy is directly involved within the southern region in three areas relevant to this Strategic Plan. These include research on: (1) effects of increased atmospheric carbon dioxide on terrestrial vegetation, (2) the fate and effects of atmospheric pollutants on forested ecosystems, and (3) the use of intensive silvicultural and physiologically-based genetic selection for maximum woody biomass production.

The goal of the carbon dioxide research program is to develop the scientific knowledge base for policy decisions on the role of carbon dioxide in global and regional effects on climate and biological systems. Direct effects of carbon dioxide on terrestrial vegetation are being studied from both the perspectives of fundamental effects of chronic increases in carbon dioxide on plant physiology, as well as long-term changes in ecosystem productivity, stability, and composition.

Through its national laboratories, the DOE conducts both in-house and extramural research on the fate and effects on forests of a wide variety of atmospheric pollutants. At Oak Ridge National Laboratory, long-term studies on deposition, fate, biogeochemical cycling, and effects of fossil fuel pollutants on forested ecosystems are conducted. Both biogeochemical and whole-tree physiological perspectives incorporated in these studies provide potentially important information for evaluating effects of interactive chemical and physical stresses on southern forest ecosystems (See Appendix for more information).

The DOE Short - Rotation Woody Crops Program is developing the silvicultural, physiological, and genetic basis for intensive cultivation of tree species as energy crops. The tree- and stand-level ecophysiological models developed to support this program offer potentially useful tools for studies of environmental interactions in intensively managed forest systems.

G. USDA AGRICULTURAL RESEARCH SERVICE

The USDA's Agricultural Research Service (ARS) conducts studies on the effects of atmospheric components on agricultural productivity and environmental quality throughout the United States. The ARS is generally concerned with all aspects of agricultural production. They have a responsibility to help solve current problems faced by producers; in addition, they have an obligation to undertake research that will serve the long-range interest of the agricultural sector. The protection, preservation, and enhancement of U.S. agricultural potential is of major importance to the programs developed through this component of the USDA.

Scientists at the ARS Research Unit located in Raleigh, North Carolina focus their research on the impact of atmospheric deposition on agricultural crops and forest trees. The principal areas of emphasis include:

1) Understanding the effects of atmospheric contaminants (including ozone, sulfur dioxide, and nitrogen oxides) on agricultural crops;

2) Understanding the effects of acid precipitation on agricultural crops and forest trees;

3) Understanding the effects of elevated carbon dioxide concentrations on plant growth and development;

4) Development of methods [especially open-top chambers and continuously stirred tank reactor (CSTR) systems] for controlled exposure of crop plants and forest trees to gaseous air contaminants and simulated acid precipitation;

5) Determination of the economic impact of gaseous pollutants on agricultural crops [as one of five major centers in the National

Crop Loss Assessment Network (NCLAN) sponsored by the US Environmental Protection Agency];

6) Determination of the effects of mixtures of atmospheric chemicals on plant growth and development;

7) Understanding the effects of biotic and abiotic stresses on the response of plant to atmospheric chemicals; and

8) Development of the Air Quality Research Library covering the world's literature on the effects of atmospheric chemicals on agricultural crops and forests.

H. TENNESSEE VALLEY AUTHORITY

The Tennessee Valley Authority is engaged in various research projects on the deposition and effects of airborne acids and other air pollutants on forests in the South. The purpose of this research is to assess the extent and magnitude of any damage; provide both an understanding of the processes responsible for such damage and a basis for mitigative action; and develop baseline data on pollutant-sensitive regions for evaluating the effectiveness of mitigation and control measures. Another objective of this research program is to determine the damage that is occurring, or that is likely to occur, in the Tennessee Valley region as a result of acid deposition, and to recommend programs for mitigating this damage.

I. NATIONAL SCIENCE FOUNDATION

The long-term Ecological Research Program of the National Science Foundation (NSF) supports ecosystem research at several sites in the southern United States. A baseline or core-measurements component of the program requires participating sites to routinely measure key environmental and biological parameters. Most, if not all, of the sites are part of the NADP. All sites have experiments in progress designed to examine ecosystem-level processes which could contribute to our understanding of the effects of various atmospheric pollutants on ecosystem functions. Consideration is being given to use of certain of these sites, (e.g., USFS Hydrologic Laboratory) for conducting manipulative experiments at the population and ecosystem level.

VII. IMPLEMENTATION

The intention of the Strategic Plan is to provide a framework for integrating existing and future research related to forest ecosystems and atmospheric pollution. Accordingly, implementation of the strategy will require an organization allowing both management of a core funding base and coordination with related Programs. As presently described, the core funding will be the Forest Service FAI/PRP budget allocated to the Southeastern and Southern Stations. Included in this base budget are funds for cooperators outside the Forest Service through the standard agreement arrangements. Both Stations' funding requests will be coordinated to be

consistent with priorities established within the Strategic Plan. Some general guidelines are:

1) The USDA Forest Service, Southeastern Forest Experiment Station will have the lead in coordinating southern forest ecosystem research and application.

2) Program Managers will be identified to provide leadership for two aspects of the Plan: mechanistic/empirical research and monitoring. They will be centrally located, in association with a Forest Service office, to facilitate administrative support.

3) An ad-hoc Advisory Committee will be established, to be composed of representatives from collaborating agencies, institutions, and universities. The role of the committee is to provide policy guidance, and to identify emerging areas of interest.

4) A Technical Committee will be established by the Managers to assist in setting research priorities. The Committee will review Program status on annual basis and make recommendations for future work.

5) Approximately 5-10% of the annual budget will be set aside for exploratory research. These projects will be selected following an open solicitation within the region for proposals.

6) Project funding external to the Forest Service will be through Cooperative Agreement or Interagency Agreements.

7) All projects will be required to submit quarterly updates and annual progress reports. (The latter can include workplan revisions for approval.)

VIII. DATA QUALITY ASSESSMENT

The development and implementation of a Quality Assurance (QA) activity is important to this program in order to document the quality of measurements and observations obtained from research and monitoring projects and to set achievable data quality goals. The principal objective of the QA Program is to assure that measurements are carried out such that the data produced are of known quality and within specified limits of uncertainty. This increases confidence in the assessment of the effects of atmospheric pollutants on forest ecosystems. The measurement systems must be in a state of statistical control to justify probability statements. This is attained by Quality Control (QC) procedures which reduce and maintain random and systematic error, and by QA procedures which monitor and evaluate the quality of the data produced.

Implementation of a QA program within the research and monitoring goals calls for the development of a two-tier management structure coordinated by the Southeastern and Southern Experiment Stations. The first tier entails the commitment of Program management to a QA policy and sets forth QA technical experts who will be involved in the Program assessment activities, and will establish the overall policies, organization, objectives, and functional responsibilities for achieving data quality goals. The four major steps to initiate QA policy in FAI/PRP include: (1) explicitly state the purpose of establishing QA, (2) describe personnel and resources

committed to performing QA, (3) identify projects which will require a detailed plan of work and QA guidelines, and (4) describe how the effectiveness of the QA activities implemented will be tracked and evaluated.

The second tier of the management structure will consist of a QA Unit Leader, who will implement the QA/QC policies established by the Program management. The QA Leader will serve as a technical support for the Program Manager in the implementation of program goals, as an educational service to researchers in the development and implementation of QC procedures within individual projects, and finally as a means for reporting data quality, via program-wide QA activities, in program assessment activities. This last activity is especially important since the program is designed to maintain the information base used by resource managers and environmental regulators to ensure the multiple-use goals of forested ecosystems.

The primary goal of the QA Leader will be to assist the Program Manager in the identification of environmental and research parameters, recommended methods of data collection, and data quality objectives. These tasks will be aided by the existing QA guidelines which were developed at the onset of the Forest Response Program. These guidelines identify Recommended Operating Procedures and Data Quality Objectives for many experimental variables in the areas of analytical measurements, site classification and field observations, exposure technology, and physiological measurements. These documents will be reviewed for use by the FAI/PRP participants and will be revised as research data become available within the Program.

Secondly, QA will assist researchers in the development of a plan of work which defines the data quality of variables measured or observed for the individual projects. The plan specifies the policies, organization, objectives, and QA/QC activities required to achieve the data quality goals of the project and program. It describes how all data will be assessed for precision, accuracy, representativeness, completeness, and comparability. The plan ensures that all data generated be thoroughly documented. The plan will provide sufficient detail to allow an independent assessment of compliance with QC procedures. The quality of the data can then be judged on the basis of quantitative accuracy and on the assignment of statistically supported limits of uncertainty. This allows scientists and decisionmakers to apply the data with confidence and a stated estimate of the true value of the measurement. The plan of work will be jointly approved by the Program Manager and QA personnel prior to implementation and will be revised and updated on an annual basis.

The third task of QA is to implement data quality assessment procedures which monitor the QC procedures and evaluate the quality of the data produced. Quality Control procedures are best monitored through a organized program of individual on-site project reviews. The review process involves both a general survey of current work and a detailed investigation of critical aspects of the measurement systems. It also serves as a forum for the interaction of researchers with Program management to assess if the quality of the data being produced is adequate for the data use requirements.

IX. TECHNOLOGY DEVELOPMENT AND TRANSFER

Technology development and transfer efforts must be coordinated with research project planning and the reporting of results. Recommendations for the delivery of research results to the forest manager include:

1) Direct efforts to identify and transfer current research results with the potential for improving the health and productivity of southern forests.

2) Involve forest-resource managers, research scientists, and technology development and transfer specialists in the identification of information needs and the research priority setting process.

3) Transfer technology concurrent with its development.

4) Require that all research proposals for funding address the following questions: (a) To whom is the research important? (b) What net benefit will the clientele and society receive if the research problem is solved? (c) What is the likelihood that the research will be successful and when can results be expected? and (d) How will the research be conveyed to the users? Thus, the technology transfer process will be a major consideration in the research proposal evaluation process.

X. PROJECTED BUDGET NEEDS FOR CORE USDA FOREST SERVICE EFFORTS

The following budget reflects funding needs for the core USDA Forest Service effort, that is, research and monitoring that can be done using existing expertise by agency scientists or cooperators. This includes extramural cooperative agreements. Costs are estimated based on current costs and assuming one scientist year (SY) = $200,000. The **TOTAL** column shows the funding available or needed in a given activity, including both the Forest Service budget and that needed from other sources (e.g., Environmental Monitoring and Assessment Program and Southern Oxidants Study). These Programs are still in development and exact funding levels are not available. In addition, the **TOTAL** includes an estimate for funds currently spent within a subject area by universities, forest industry, states, and non-air pollution research within the Forest Service. For example, there already exists extensive research on tree response to water/drought stress, which can be used within a climate change context. Out-year funding for years 2 and 3 of the Plan are indicated; budgets beyond 3 years are difficult to project as results generated between now and 1993 may change the prioritization.

Table 1. Estimated Budget (In Thousands) for Research Area by Priority Area: Core Funding and Estimated Total.

	FS Year One (1991)	Estimated Total (FY91)	Year Two (FY92)	Year Three (FY93)
1. Effects on Ecosystems				
A. Physical Changes				
Priority I	2,700	3,000	Increase	Increase
II	500	1,000		
III	300	300		
B. Chemical Changes				
Priority I	2,700	5,000	Increase	Level
II	500	1,200		
III	400	1,700		
C. Interactive Stress				
Priority I	1,100	2,000	Increase	Level
II	500	600		
III	300	1,000		
2. Effects on Atmosphere				
A. Biogenic Emissions				
Priority I	600	1,500	Level	Level
II	300	1,500		
B. Land Management Influences				
Priority I	900	1,000	Level	Increase
II	400	3,000		
3. Assessment of Long-Term Changes				
Ecosystem Monitoring				
Priority I	1,500	8,000	Increase	Level
II	800	3,200		
III	350	1,500		
4. Ecosystem Modeling				
Prediction of Response				
Priority I	1,000	2,300	Increase	Increase
II	500	1,000		
III	200	400		
TOTAL I	10,500	22,800		
II	3,500	11,500		
III	1,550	4,900		

APPENDIX

DESCRIPTION OF CURRENT AND PLANNED AGENCY, INDUSTRY AND INSTITUTIONAL RESEARCH ACTIVITIES

This presentation of program descriptions is not meant to be all-inclusive of programs which are in planning for the 1990's. It does provide a brief overview of these programs and projects which will contribute to our understanding of physical and chemical climate impacts on forests in the South. Additional information can be obtained from the Agency or institution. Figure 3 shows the location of research and air quality monitoring activities in this region.

I. USDA FOREST SERVICE

A. FOREST-ATMOSPHERE INTERACTIONS/PRIORITY RESEARCH PROGRAM

Anticipated changes in the physical and chemical nature of the Earth's climate are likely to have significant impacts on the Nation's forests and related ecosystems. These changes will require the USDA Forest Service and other land managers to respond with effective management practices to protect and maintain forest health and productivity. The development of new management techniques, however, is limited by the current lack of sufficient information on the current state of U.S. forests and by an inability to predict and detect changes in forest health and productivity due to climate change.

The Forest-Atmosphere Interaction/Priority Research Program (FAI/PRP) is being initiated to build upon existing research efforts and to use a complete ecosystem perspective when examining the interactions between forests and the atmosphere. The objective of the FAI/PRP is to provide the scientific basis to address three broad questions on the effects of physical and chemical climate change on forest, range, and related ecosystems:

1) What processes in forested ecosystems are sensitive to physical and chemical changes in the atmosphere?

2) How will future physical and chemical climate changes influence the structure, function, and productivity of forests and related ecosystems?

3) What are the implications for forest management; and how must forest management activities be altered to sustain forest health and productivity?

1. <u>Program Research Elements</u>

Two planning workshops during 1987-89 have produced a set of research elements upon which to focus the resources of the FAI/PRP. These elements fall under four general categories: (1) effects of the atmosphere on ecosystems; (2) effects of ecosystem changes on the atmosphere; (3) assessment of long-term changes; and (4) ecosystem modeling.

2. Research Priorities

The research elements were assigned first-, second-, and third-order priorities based on future forest management needs as perceived by the Forest Service participants.

First-Order - The three first-order priority elements involve research that addresses Forest Service mission statements and critical needs for resource management. The issues included apply across the entire program rather than to individual resource priorities.

- Energy, Carbon, Water, and Nutrient Cycling
- Long-Term Ecosystem Monitoring
- Ecosystem Management Models

Second-Order - The three second-order priority elements include research that addresses the current issues of concern more specifically but still focuses on basic research questions.

- Species Life Histories and Distributions and Community Composition
- Water Yields, Erosion, and Sedimentation
- Changes in Forest Area

Third-Order - The remaining third-order priority elements focus on specific ecosystem effects and additional research support activities. These elements involve a more regional and station-level perspective.

- Fire Severity and Occurrence
- Aquatic Ecosystems and Fisheries
- Domestic and Wildlife Species
- Microbes, Plant Pathogens, and Insects
- Quantity and Quality of Wood
- Mass, Energy, and Momentum Transfer
- Emissions of Forests and Forest Fires
- Spatial and Temporal Scale Interfaces
- Simulation and Management Model Interfaces

B. SOUTHEASTERN FOREST EXPERIMENT STATION

1. Southern Commercial Forest Research Cooperative

Intensive Research Sites

The Southern Commercial Forest Research Cooperative has developed five Intensive Research Sites located across the South in North Carolina, South Carolina, Florida, Alabama, and Texas. The primary objective of the Intensive Research Sites is to determine the influences of acidic precipitation and ozone on the growth, nutrition, and physiology of southern pines under field conditions. Five locations across the South were selected from a total of twelve proposed, specifically to represent the regional distribution of southern pines, and to emphasize the three most important commercial species: loblolly, shortleaf, and slash pines. The sites cover the major physiographic regions supporting southern pines: Piedmont, Upper and Lower Coastal Plain, and the Western Gulf. These sites are conducting atmospheric monitoring, exposure/response research, and mechanistic research. The chamber sites were located so that work could be conducted in mature stands in tandem with the open-top chamber studies. This enables the study of plant physiological response in both mature trees and in seedlings under similar environmental conditions. At the present time, efforts are being concentrated on the chamber studies; however, research could readily be expanded now that the sites are fully operational.

Following the initial design, seedlings have been planted in natural forest soil within open-top chambers located in cleared forest sites. Air quality and meteorological information is being obtained at most sites. Acidic deposition and ozone treatments are being applied in a factorial combination design for three years. Measurements taken periodically include: tree growth, biomass, physiological and nutrient measurements, and soil chemical properties and processes.

The research conducted at the five Intensive Research Sites will provide:

1) information with which to develop empirical models to estimate the effects of precipitation acidity and ozone exposure on pine growth responses,

2) a test of any interactions between acidity of precipitation and ozone,

3) evaluations of mechanisms of action of acid precipitation and ozone, and

4) information which could contribute to the development of a regional assessment of impacts.

By 1991, when the SCFRC will have been terminated, the sites will have three years of continuous air quality monitoring, plus the most complete data set available for assessing tree species response to air pollution stress. These locations already are emphasizing, in their research, several of the first-order priority research needs discussed earlier. They can readily be expanded to include several emerging needs identified as important in this Plan.

Controlled/Uncontrolled Exposure Studies

A number of other important studies are ongoing in the SCFRC. At the University of Georgia in Athens, two major studies are underway for the SCFRC. The studies are designed to address, using established trees, the growth impacts of two key responses to air pollution: (1) a reduction in leaf area and (2) a reduction in net carbon exchange per unit leaf area. Study I is determining the influence of ambient air and four levels of ozone on carbon exchange capacity and leaf area dynamics for upper-canopy branches of 11-year-old loblolly pine trees. The outputs from this study will be exposure/response curves for carbon exchange capacity, leaf area accretion, senescence, and branch growth.

Study II focuses on describing, for whole trees, the impact that changes in leaf area will have on above-ground biomass production potential. This is being accomplished by establishing four levels of leaf area and monitoring the net carbon exchange capacity and tree growth potential for the range of leaf area present in the study trees. The key output from this loblolly pine study will be a model which relates above-ground biomass production to leaf area, net carbon exchange capacity and environmental conditions.

At Oak Ridge National laboratory in Oak Ridge, Tennessee, laboratory and field chamber studies completed in 1988 evaluated growth and physiological response of loblolly pine to interactive stress from ozone and simulated acidic rain. Scientists at North Carolina State University in Raleigh are studying the growth response of pine seedlings to varying levels of acidic rain and different anionic concentrations. The SCFRC is also supporting uncontrolled field studies on one of EPRI's Integrated Forest Study sites (See page 50).

2. **Forestry Sciences Laboratory - Coweeta, North Carolina**

Over 50 years of continuous hydrologic research at the Coweeta Hydrologic Laboratory have documented streamflow responses to forest cutting and regrowth against a background of seasonal, annual, and longer term climatic variability. Short-term fluctuations of temperature and precipitation, and energy balance differences due to slope orientation have been shown to influence streamflow responses. Recent analyses of the long-term Coweeta databases have suggested trends of increasing streamflow and decreasing evapotranspiration that may be related to trends in growing season temperatures. Building on this extensive base of knowledge, proposed research would elucidate the influences of climatic variability and change on streamflow amount and timing from natural and managed forests. A second phase of this study will apply knowledge of streamflow-climate relations to data on climate variability at other sites in order to extend results to a wider range of conditions.

The Coweeta long-term precipitation and stream chemistry record has proved invaluable for detecting trends in solution chemistry in relation to atmospheric deposition and for separating changes in stream chemistry due to natural processes from those resulting from human activity (e.g., air pollution). Proposed research will continue the present monitoring network on reference watersheds (8 precipitation and 10 stream gaging sites, 12 ionic constituents), and will also fill gaps in the current network by

expanding the monitoring to detailed assessments of organic constituents including organic acids, dissolved organic carbon, and dissolved organic nitrogen.

Research at Coweeta is currently focused on quantifying atmospheric deposition to forest canopies, including both particulate (SO_4, Ca, Mg, etc.) and gaseous forms (HNO_3 vapor, SO_2, NO_x, O_3), using both direct and indirect sampling methods. However, present research is not addressing the transport and physiological impacts of deposited constituents. Proposed research will utilize isotopes and other experimental techniques to examine pollutant (e.g., HNO_3) fate and impacts on plant biochemistry, photosynthesis, and water relations. Studies will be conducted primarily under in situ conditions. In conjunction with short-term process-level studies of deposition impacts on tree physiology, there is a need to document long-term air quality trends and the exposure regime of various atmospheric particulates and gases in the mountainous terrain of the Southern Appalachians. Proposed research will supplement current monitoring of gaseous constituents at a base station in the Coweeta Basin by adding additional variables (such as carbon dioxide and nitrogen compounds) and with the establishment of a slope or ridge site.

Evaluating potential changes within forest ecosystems requires models that integrate individual plant responses into stand- and community-level responses. Such models will be used to pose "what if" questions regarding changes in the atmosphere, changes in water and nutrient availability, and changes in the plant matter itself (e.g., carbon allocation patterns). Growth-and-yield models must be process-based so that potential impacts of changes in the physical, chemical, and biological environment on tree growth and stand dynamics, can be evaluated.

3. Institute of Tree Root Biology - Athens, Georgia

Tree root dynamics under conditions of natural and man-made stress are poorly understood. The Forest Service, partially in support of the FAI/PRP, has created a specialized research center to serve as a focal point for multi-disciplinary and multi-institutional research on the biology of tree roots and their relationship and/or interaction with whole-tree and forest-level growth processes and the environmental conditions which affect them. Its goal is to investigate, synthesize and disseminate essential information on the below-ground portions of the forest ecosystem in order to contribute toward prudent decisionmaking on issues related to forest health, productivity and the integrity of the global ecosystem.

C. SOUTHERN FOREST EXPERIMENT STATION

1. Forestry Sciences Laboratory - Gulfport, Mississippi

Until recently, the rapid growth of the southern pine forests, coupled with the massive acreage occupied, could produce sufficient net annual increment to support the demand for timber, fiber, and related forest products. However, in recent years several factors have begun to operate to decrease the acreage and the productivity of southern forest lands, and as a result the net annual increment is beginning to decline. At the same time, demand for forest products is rapidly increasing. Genetic improvement of the southern pines will be a vital component in the effort to increase

southern forest productivity. Research conducted on pine genetics at the laboratory in Gulfport has three components related to the goals of this Program. They are (1) information on the effects of long-term climatic and edaphic conditions on the response of non-local seed sources, (2) improved procedures for incorporating genetic gain in growth-and-yield models and (3) fundamental knowledge on the number of genes, their location in the genome, and their mode of action. Under this Program, research would be accelerated to monitor changes in southern forest productivity using clonally-propagated southern pines.

There is ample evidence for genetic variation in such traits as growth, fusiform rust resistance, and pollution susceptibility. Genetic control of test material is a crucial consideration for any study of subtle yearly changes in productivity. Therefore, it is proposed to use clonally-propagated southern pines chosen from families whose growth and disease susceptibility have been well characterized in previous studies. Identical test plantings will be located at many sites across the South. Some of these will be planted as close as possible to EPA atmospheric monitoring stations to explore the relationship of growth, survival and disease susceptibility to atmospheric deposition. Sites will be obtained that are large enough to accommodate repeat identical plantings every other year for at least 10 years. This will allow the study of yearly trends at identical stages of individual tree and stand development.

2. Alexandria Forestry Center - Pineville, Louisiana

A database of over 1200 permanent plots for modeling the effects of age, site quality, stand density, and stand structure on growth and yield of pure, even-aged plantations of loblolly, longleaf, and slash pine has been expanded through periodic measurements and thinning of study plots. Additional biomass data have been collected which allow green and dry weight parameters to be included in predictive models. Through cooperative efforts, the impact of fusiform rust on growth and yield of loblolly and slash pine plantations provide new insight into the effects of genetic resistance and competition on survival of infected and uninfected trees. A model for predicting growth and yield by diameter classes of unthinned and thinned loblolly pine plantations has been completed. The need exists to study tree physiology and climatic change simultaneously within stands with preexisting long-term data bases. Within many of these long-term studies, there exists information on tree location; mortality, by year, of neighboring pines; and yearly or periodic growth data for both the missing and surviving pines. Such data sets can be combined with intensive physiological and climatic studies to produce single-tree models that predict the effects of pollutants and climatic change on southern pine growth. There is a need to develop and integrate physiologically-based individual tree growth models with stand models in order to more accurately mimic the actual biological processes occurring within trees and stands.

The opportunity now exists to begin to understand how silviculture interacts with climatic and soil factors to affect physiological processes such as photosynthesis, transpiration, and carbon and nutrient allocation. As these processes become better understood, flexible models can be developed to accurately predict forest productivity in a changing environment and for varying levels of management intensity. This basic work could be also used to interface with forest utilization, specifically on the effects of timber management on wood quality. Studies attempting to relate forest productivity declines to air pollution have been hampered by the lack

of long-term data and inadequate understanding of tree growth and physiology as affected by climatic variables. Intensive monitoring of physiological measurements and radial and shoot growth in trees and stands in various locations requires additional automated sampling equipment. The substantive databases that rapidly evolve from such tree measurements and weather collections must be amassed and summarized by automated techniques, fed directly to dedicated computers, and analyzed promptly.

A definition of physiological variables affecting sugar production and allocation in forest trees is necessary to silvicultural manipulation of these variables and construction of models for predicting productivity under a range of environmental conditions. This is particularly important in controlling forest pests that attack trees when the energy drain is high due to normal reproductive and vegetative processes.

3. Institute of Quantitative Studies - New Orleans, Louisiana

The IQS mission is to enhance forestry research and operations through the use of statistics, mathematics, and computer science. Of the two major problems currently assigned, one addresses general development of systems to predict timber growth and yield. The other problem is even more specifically related to air pollution because it recognizes that traditional statistical methods are inadequate for assessing and predicting the impacts of insects, disease, and environmental stress factors on the development of southern forests. Currently the staff includes thirteen professionals of whom seven are mathematical statisticians and the rest provide expertise in forest biometry, computers, and ecology.

Unit scientists produced the yield systems for southern pine plantations that are featured in the Forestry Handbook as well as the chapter on Mathematics and Statistics in that publication. Staff members have been instrumental in team research to quantify the impacts of fusiform rust both in predicting field performance from greenhouse tests and via adaptations of growth-and-yield models. Previous work provided discriminant analyses that identified the critical soil properties in classifying sites for root rot threat in the South. Other work developed models to explain the counts of southern pine beetles drawn to traps and involved the unit in efforts to forecast beetle damage trends.

Through special grants the unit conducted a statistical methods project for the National Vegetation Survey that initially involved a review of evidence related to forest decline and identified the need for improved analysis of tree-ring data. Subsequent research led to the introduction of the Kalman filter, computer-based processes of cross-dating tree cores, and software that has had a profound influence on evaluations related to air pollution. Another project involved the development of data pools and analytical processes to address questions of the alleged growth decline in southern forests. This project has resulted in the largest aggregation of research growth-and-yield data that has ever existed, components related to weather factors, and the development of formulations including some individual tree and process approaches.

The staff, experience, computer facilities, and data pools of the IQS provide a ready means of advancing in the difficult analysis and modeling tasks that will dominate the next phase of atmospheric pollution research.

4. Forest Hydrology Laboratory - Oxford, Mississippi

Several of the watershed studies conducted over the last decade or two have provided considerable information on changes in streamflow chemistry and water yield associated with climatic conditions in the upper Coastal Plain and Ozark-Ouachita Highland Regions. Some of the data suggest that changes in streamflow chemistry have occurred, but the sources of these changes have not been associated with specific environmental changes.

The existing watershed studies can provide excellent field laboratories for determining changes in forest ecosystems resulting from all phases of atmospheric input and interaction. A large amount of climatic data, including precipitation, temperature, humidity, and solar radiation are available for extended periods. Several related studies are providing information on changes in the chemical and physical effects of rainfall as it passes through forest canopies and forest soils and enters the streams.

These watershed studies and related university cooperative studies offer an opportunity to study the complex ecosystems associated with forests in diverse physiographic regions.

5. Institute of Tropical Forestry - Rio Piedras, Puerto Rico

Tropical forests constitute half the world's forestlands and provide food, shelter, fuel energy, and fiber to billions of people. They are among the least understood ecosystems in the world because they are extremely complex and because few scientists and institutions are dedicated to tropical forestry research. Yet, tropical forests affect global geochemical cycles (e.g., carbon, water, sulfur), and their function and productivity are believed to respond to global human changes. Scientists do not fully understand the magnitude of these interactions but there is general agreement that the role of the tropical forest is pivotal--at least with regard to the global carbon cycle. To date, most studies on tropical forests have been short term in nature, and very few have focused directly on whole ecosystem function. Work in Puerto Rico at the Luquillo Experimental Forest (a biosphere reserve and a National Forest) is a notable exception, with 100 years of research tradition and a strong focus on hydrologic, geomorphic, atmospheric, ecophysiologic, and whole ecosystem phenomena. This forest is well underway to being designated a National Science Foundation long-term ecological research site.

Because Caribbean forests are exposed to constant tradewinds interrupted by periodic events of acid rain and dust deposition from the Saharan region, they offer a unique opportunity to study ecosystem coupling with, and response to, atmospheric factors (e.g., acidity, nutrients, and gaseous composition). We propose to study forest and individual tree responses to discrete events, when these factors are known to change, as a first step toward developing basic understanding of interaction mechanisms. Previous research on cloud and rainfall chemistry in the forest has documented the occurrence of discrete events in which atmospheric inputs to the forest change from the norm. At these times, acidity changes (usually increases), nutrients in clouds increase, and carbon dioxide may increase. The effect that such changes have on evapotranspiration, photosynthesis, leaching from canopy and soil surfaces, and quality of runoff can all be studied with available facilities by simply expanding the scope of current studies and increasing atmospheric monitoring and modeling. From the analysis of a sufficient number of events, we propose to develop forest and

tree response models that can be tested experimentally. Also, monitoring of atmospheric phenomena over long time periods will provide needed data to validate models, assess significance, and extrapolate to other parts of the world.

D. REGION 8

1. Center for Forest Environmental Studies - Macon, Georgia

The Center (originally named Air Pollution Testing Center) was constructed in 1987/88, by the USDA Forest Service, (Region 8 - Forest Pest Management and the Southeastern Forest Experiment Station). The mission of the Center is to provide a state-of-the-art facility to increase our understanding of how trees and other forest resources respond to changing environmental stress, and to help make recommendations for forest management, under these stresses, to maintain healthy and productive forest ecosystems for the future. The Center is located near Macon, Georgia on the property of the Georgia Forestry Commission, and consists of a 2,000 square foot headhouse and a 6,000 square foot greenhouse. The greenhouse is divided into 6 large bays, with the entire inside air under filtration to remove pollutants. The internal temperature is closely regulated, to within 3°F of ambient air. The Center staff and cooperators will include those with expertise in air pollution effects, genetics, plant physiology, soils, and greenhouse culture of tree seedlings. Exposure equipment includes 12 rain simulators for studying acidic rain effects, and 20 Continuously Stirred Tank Reactors (CSTRs) for evaluating effects of gaseous pollutants. The CSTR system will allow testing of temperature and relative humidity changes, in combination with air pollutants. The computer-control system installed for the CSTRs makes it one of the most sophisticated facilities in the country. This type of facility is an excellent complement to field research, as it enables the scientist to focus on a single factor or factors under controlled conditions. In addition to mechanistic research, the Center can provide for rapid testing of many types of plant material to air pollution impacts, including herbaceous plants, and mosses.

2. Resistance Screening Center - Bent Creek, North Carolina

The Resistance Screening Center at Asheville, North Carolina was established in 1973 to help meet the threat of fusiform rust. The facility is made up of 5 greenhouses covering 7600 square feet, with 2400 square feet of support facilities. The facility currently offers screening for fusiform rust on loblolly, slash and longleaf pines, and pitch canker on slash pine as a service to tree improvement specialists, seed orchard managers, scientists, and others in government agencies, research institutions and private industry. This greenhouse screening for fusiform rust and pitch canker offers a quick, reliable service that can produce standardized relative resistance data under very uniform, controlled conditions. The Center has screened over 10,000 seedlots since it was established.

With the current design of 120 trees per seedlot, the Screening Center can process 900 seedlots per year. A part of the seedlots each year are used to improve and enhance the work at the center or to assist researchers with their work. Because of the quality control and uniformity of testing, the facility offers a unique opportunity to study the effects of environmental and biological interactions. By holding all but one variable

constant, the resulting change can be quickly and effectively assessed. Even though the facility does not have the ability to change some variables, such as as air pollution, this kind of exposure can be done as a pretreatment and then sent to the Center for screening. An example would be the pretreatment of seedlings at the Macon Center for Forest-Environmental Studies, with subsequent screening at the Resistance Screening Center. This Screening Center offers an opportunity to validate current theories and test new theories as they emerge.

E. NORTHEASTERN FOREST EXPERIMENT STATION

1. Spruce-Fir Forest Research Cooperative - Broomall, Pennsylvania

The Forest Response Program's Spruce-Fir Research Cooperative (SCFRC) is studying the impact of air pollution in high-elevation forests of the Appalachians. Two major conceptual approaches are used: the epidemiological and the physiological/ecological. The general research strategy for the epidemiological studies is to uncover patterns of forest condition which then lead to formulation of hypotheses to be tested by the physiological/ecological studies. Since the results of these studies must be incorporated into an understanding of the spruce-fir stands and ultimately the red spruce-fir ecosystem, a modeling approach is also being utilized. The modeling approach assists in (1) hypothesis generation, testing and refinement; (2) research synthesis and integration; and (3) estimating the effects of atmospheric deposition in red spruce-fir stands.

The Spruce-Fir Cooperative's efforts in the South focus on assessing current condition of these forests through the establishment of permanent inventory plots where data on soils, pathogens, meteorology, and pollutant concentrations are collected.

II. U.S. ENVIRONMENTAL PROTECTION AGENCY

In September 1987, at the initiative of EPA Administrator Lee Thomas, the U.S. Environmental Protection Agency's Office of Research and Development directed its scientists to develop an integrated environmental research strategy to improve the Agency's ability to assess the risks to natural ecological systems at the regional scale from current and emerging environmental pollutants. Three primary elements were needed to develop this strategy:

- an ecological status and trends program that serves to characterize, classify, and quantify trends in the status of ecological resources and pollutant exposure;
- a core ecological research program to develop tools to predict ecosystem-level responses to incremental changes in anthropogenic activities; and
- an ecological risk assessment program that allows monitoring and research outputs to be integrated into quantitative estimates of ecosystem-level risks from regulatory policy alternatives.

The Office of Research and Development developed a coordinated strategy that utilizes a tiered approach similar to that used in risk assessments for single pollutants. This approach recognizes that, because EPA has insufficient monitoring and research resources to address all ecological problems, it must have an objective basis for identifying the highest priority issues of concern and determining their current or potential severity on a regional basis. This strategy also recognizes the need to utilize, as fully as possible, current monitoring programs conducted by EPA and other Federal and non-Federal agencies and organizations, working cooperatively to fill any critical data gaps.

In the proposed tiered approach, available biological and chemical monitoring data will be used wherever possible to identify problems and corresponding geographic areas that appear to be at highest risk. High-priority systems will serve as the focus for intensive evaluation of baseline conditions and trend monitoring in the higher tiers, and for research leading to the development of predictive models. Lower priority systems will be subjected to less intensive, surveillance-level monitoring. Monitoring programs will be developed or supplemented to fill data gaps that are found to prevent minimally acceptable surveillance.

A. ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

The first proposed step in the development of the integrated ecological research strategy is the creation of the Environmental Monitoring and Assessment Program (EMAP). This program has been proposed by the EPA to begin in FY 1990 to complement its Acid Deposition, Global Climate Effects, and Stratospheric Modification Research Programs.

The goal of EMAP is to identify, collect, organize, and analyze environmental monitoring data and report periodically to the Administrator on the current status and trends in indicators of the condition of the nation's ecosystems.

Combined with the expertise of the appropriate laboratory, program, and policy office staffs, these data reports and interpretive summaries will enhance the Agency's ability to identify and evaluate emerging environmental issues, to focus scientific assessment programs on high-priority issues in the regions and ecosystems of highest potential concern, and to periodically evaluate the validity of the scientific models upon which risk management strategies are based.

In order to accomplish the program goals, EMAP will be designed to meet the following objectives:

1) Make maximum use of existing monitoring programs to meet EPA's ecological assessment needs and design a program to efficiently fill the critical data gaps.

2) Establish baseline conditions and monitor trends in pollutant exposure levels and vital indicators of ecosystem condition for forest, wetland, near-coastal, inland surface water, and agricultural ecosystems on a regional scale.

3) Seek and identify relationships between indicators of ecological condition and pollutant exposure that should be considered for in-

depth risk assessments by EPA program offices, or that could serve as the basis for important testable research hypotheses or empirical management models.

4) Provide a flexible and cost-effective mechanism for responding in a timely way to the need to assess status and extent of rapidly emerging issues of public concern.

Pollutant "exposure", as used here, may include ambient levels of toxicants, nutrients, microorganisms, or geophysically active substances present in air, wet and dry deposition, surface-and groundwater, soil and/or biological tissues as a result of human activities, that can result in presently unanticipated effects on ecosystems. Ecological indicators may include direct or surrogate measures of current or future levels of socially valued ecosystem products, structural or functional ecosystem characteristics, including sustainability, or impacts on adjacent ecosystems.

1. Implementation

The Environmental Monitoring and Assessment Program is planned to be implemented in three phases:

- Phase I (present-October 1989): Preparation and Review of Phase II Research Plan
- Phase II (October 1989-August 1991): Assessment and Design
- Phase III (September 1989-continuing): Phased Implementation, beginning with Pilot Testing in 1992

The primary outputs of EMAP would be annual environmental statistical reports that describe the regional status of the various indicators and indices chosen for inclusion, and statistical analyses of regional changes and trends. Such results are expected to come from a combination of periodic regional surveys (re-measurements) and more intensive data time-series from selected regionally-representative research sites. More extensive interpretive assessments are expected to be produced at three to four-year intervals.

2. Approach

A number of the tasks that are currently planned for development in the Phase II Research Plan are summarized briefly below. Although the tasks are listed in approximately sequential order, many can be developed in parallel.

1) Develop a data management system that catalogs appropriate monitoring programs and their associated databases and ensures efficient access to quality-assured data in a convenient and compatible format.

2) Classify ecosystems into categories that could be monitored using similar measurement techniques and that would respond similarly to pollutant-related stresses.

3) Conduct a screening-level evaluation using available data and studies to identify high-risk or already damaged ecosystem categories and to identify critical data gaps.

4) Develop, evaluate, and standardize measurement protocols for indicators that best quantify the vital structural and functional aspects of ecosystem condition.

5) Evaluate the applicability of current monitoring network designs, measurement methods, and quality assurance programs to emerging environmental issues.

6) Design and assist in the implementation of cost-effective monitoring programs that fill critical data gaps.

7) Design the annual data reports and summary statistics.

The Phase II Research Plan, which is being readied for peer review in mid-1989, will describe the research needed to determine whether a program meeting the design objectives of EMAP can begin phased implementation on a pilot basis in 1992, and if so, to propose a cost-effective design. If implemented, the program will begin producing environmental statistics on an annual basis by 1994.

B. TROPOSPHERIC OZONE PROGRAM

The research program, "Effects of Tropospheric Ozone on Forest Tree Species", is being conducted to support the legislative mandate of the EPA in setting national ambient air quality standards (NAAQS). Both extensive and intensive studies will be conducted. Forest species will be selected to ensure national coverage, trees of economic and ecological importance, and potential risk to ozone impact based on geographical location of species and occurrence of elevated levels of ozone. Studies are designed specifically to address the issue of changing air quality scenarios, the mechanistic basis for interaction of ozone and trees as a function of age and/or size, and the influence of exposure, environment and genetics on the response. The research program will provide EPA's Office of Air Quality Planning and Standards (OAQPS) information relevant for: (1) ozone risk assessment and (2) exposure indices relevant for trees. An index or measure of exposure for the NAAQS is needed that will reflect the cumulative, long-term impact of ozone on the life of a tree or a forest. The information will consist of both empirical exposure-response functions for multiple species and model-based simulations of tree growth response to changing levels of ozone.

The research plan completed a successful peer-review (7/18/88) and a follow-up workshop was held (7/19-20/88) to address the concerns of the peer-panel. Research as described in the plan has begun, and other work will begin after October, 1988. All research work done off-site will be solicited through the process of RFPs and awarded based on peer-review of the proposals. This program will keep abreast of work done through other agencies to aid coordination of overall objectives of this program and to meet the needs of the client office OAQPS in setting a NAAQS.

C. IMPACTS OF GLOBAL CLIMATIC CHANGE ON FOREST COMPOSITION AND DISTRIBUTION

1. Problem Statement

General circulation models project a mean annual global warming of 1.5 to 4.5°C within the next century. Such conditions would be the warmest of the last 125,000 years and the most rapid rate of global temperature change in at least the last 10,000 years. In forest ecosystems, the consequences of a rapid warming may include large scale die-back of susceptible individuals and species, major shifts in species distributions, and increases in catastrophic disturbances. Alternatively, warm tolerant species and species favoring disturbed sites may experience increased recruitment. Forest managers and policymakers do not currently have the information necessary to effectively respond to significant climatic change impacts.

2. Objectives

This research will assess potential losses of forest resources in response to global climatic change and increased carbon dioxide. Forest resources (including wildlife and biological diversity, in general) that are particularly at risk will be identified. The magnitude and mechanisms of changes in composition, productivity, and species ranges will be examined and potential management strategies for minimizing significant losses (e.g., tree planting) will be assessed. In addition to the effects of climate and carbon dioxide on forests, the indirect effects on forests and the impacts on watershed yield, water quality and non-point source runoff will be examined. The long-term goal is the development of a capability to predict climatic change impacts on forest occurrence and function at stand, landscape, and regional scales and the feedback of these impacts on regional land-use and water quantity and quality.

3. Scope

The proposed research will provide projections of forest growth and development in all forested regions of the United States under various scenarios of climatic change. Mechanistic models of forest development will be built that are driven by climatic variables, including temperature, precipitation, solar radiation, and certain air chemistry variables. At first, model parameters will focus upon specific site conditions (e.g., soils, initial stand conditions) and initial simulation runs will examine forest dynamics under a range of climate scenarios. Later model development will extend to larger landscapes composed of mosaics of stands and other land uses and will incorporate disturbance regimes including fires, insect outbreaks, and extended soil drought, and ecosystem responses such as water yield, biogeochemical cycles or other variables reflecting possible consequences of changing climates. Impacts of forest change on biological diversity will be a major consideration in the research.

4. Approach

Specific studies proposed for possible implementation over the next five years are as follows:

1) Potential shifts in the ranges of major United States tree species by the year 2030 will be assessed and mapped using response surfaces. This method first involves compiling temperature and precipitation characteristics along the present range boundaries of each species. Secondly, the species potential range under a new climatic regime is projected based on the spatial shift in the distribution of these boundary values.

   Future forest composition and regional patterns will also be projected by extrapolating from response surfaces of modern pollen percentages. In this case, the distribution of modern pollen is examined rather than tree distributions. Projections of future pollen distributions will be based on future climate scenarios.

2) The pattern of forest community occurrence and production in relation to a range of environmental variables (including climate) will be quantified using direct and indirect gradient analyses. Satellite imagery, forest survey and habitat type data, published information, and newly collected data will be used to map the current distribution of U.S. forest types. This pattern will be correlated with climatic, landscape, and land use variables to produce conceptual models of forest type occurrence in relation to environment. Based on these relationships, projections of shifts in the distribution of forest types will be made in response to climatic change. This essentially represents an extension of the response surface methodology of study #1 from individual trees to communities.

3) Gap-phase forest dynamics models will be generalized to include projections of both local and regional forest composition and production. These models will be used to simulate forest responses climatic change across a range of sites in selected forest regions of the U.S. Study sites will be located where long-term data on tree recruitment, growth, and death are available for model verification. In addition to climatic stress, the models will consider disturbance, silvicultural treatments (including reforestation), competition for limited resources, hydrology, biogeochemical cycles and the possible dispersal of species into each region as conditions become favorable for their establishment and growth. Direct effects of carbon dioxide will be evaluated based on sensitivity analysis (using the models) and exposure experiments (both from the literature and new research).

4) Impacts on biological diversity of forests will be addressed using a variety of approaches that incorporate modeling, literature survey, synoptic pattern analyses and other approaches. The approaches will range from broad-scale survey and qualitative prediction to particular case studies of species or regions or reserves.

5) Changes in wood production are potentially a major impact of climatic change on economic forestry. Covariation between tree ring widths and climatic patterns will be used in the detection of regional trends in growth.

6) North American forest policy questions relating to climatic change effects will be addressed in a white paper workshop attended by experts from Canada and the United States.

III. SOUTHEASTERN UNIVERSITIES RESEARCH ASSOCIATION

The Southeastern Universities Research Association (SURA) is a 39-member university consortium whose goals are to foster excellence in scientific research throughout the Southeastern United States to help meet national science and technology goals. The main focus is on supporting, developing and/or managing projects or facilities that are too large or too diverse for one university to undertake. Although established only in the past decade, SURA has significantly altered the way science in the Southeast can be addressed. Its first activities have established a large electron accelerator and nuclear physics facility and the largest regional super-computer network in the United States.

Recently SURA has established a new initiative to examine regional environmental change issues, concentrating on global climate change. SURA's approach will be to examine region-wide issues related to global climate change, particularly in terms of examining key interface problems. These interfaces problems are those identified by the International Geosphere-Biosphere Programme (IGBP) as being the most crucial for understanding how our global environmental system functions. Among the most important interface questions to be examined are those related to biospheric, atmospheric and hydrologic functions of southeastern landscapes. The first SURA-facilitated proposal will investigate interactions between the atmospheric chemistry and terrestrial biosphere throughout the Southeast, concentrating on a variety of process and landscape and mesoscale models to organize the research and development effort.

The SURA global change initiative will not become involved in single-disciplinary oriented research, historically the domain of individual institutions. Rather, its main efforts will be dedicated to solving problems that cannot ordinarily be attached by single universities, or small numbers of cooperating researchers or institutions. The strength of SURA will be to examine large-scale problems requiring expertise from many universities throughout the Southeastern United States. In this way, a special role, or niche, for SURA in global change issues will evolve through assembling state-of-the-art programs focusing on the interfaces as called for by IGBP.

IV. SOUTHERN OXIDANTS STUDY

In June, 1988, a multidisciplinary workshop entitled "Atmospheric Photochemical Oxidants: A Southern Perspective" was held at the Georgia Institute of Technology under the leadership of Drs. Michael Rodgers, William Chameides, and C.S. Kiang. The Executive Summary of Discussions and Research Recommendations developed at the workshop (Rodgers and Chameides, 1988) includes recommendations for a five-year multi-institutional research and monitoring program, the Southern Oxidants Study (SOS) with the following objectives:

1) Establish a network of air-quality monitoring sites in various areas in the southern United States to determine spatial and temporal trends in chemical meteorology and chemical climatology, including both natural and human sources of airborne hydrocarbons.

2) Determine and quantify the role of natural hydrocarbons, anthropogenic hydrocarbons, and nitrogen oxides in the formation of ozone and other photochemical oxidants in the atmosphere of various urban and non-urban areas of the southern United States.

3) Determine the severity and extent of injury by ozone, and the extent of genetically-controlled variability in resistance and susceptibility to ozone and other photochemical oxidants, among selected crop plants, forest trees, and ornamental plants in various urban and non-urban areas of the southern United States.

4) Characterize the ozone exposure of humans pursuing various styles of outdoor life in various urban and non-urban areas in the southern United States.

5) Evaluate alternative strategies for management of ozone and other photochemical oxidants and their injurious effects in various urban and non-urban areas of the southern United States.

Substantial mutual advantage will result if the SOS planning and exploratory research activities described above are coordinated with other research being conducted or planned in connection with the following programs:

1) The "Forest-Atmosphere Interactions/Priority Research Program" (FAI/PRP) currently being developed by the USDA Forest Service;

2) The current and planned national program on effects of atmospheric stresses (including photochemical oxidants) on agricultural crops being conducted and planned by the USDA Agricultural Research Service;

3) The expanded national program of research on effects of photochemical oxidants on vegetation currently being planned by the Ecological Research Laboratory of the US Environmental Protection Agency in Corvallis, Oregon;

4) The "Ecological Monitoring and Assessment Program" (EMAP) currently being planned by the US Environmental Protection Agency; and

5) The Response of Eastern Forests to Multiple Pollutants currently under discussion in the US Environmental Protection Agency's Global Climate Change Program.

V. USDA AGRICULTURAL RESEARCH SERVICE

The USDA Agricultural Research Service (ARS) is developing the conceptual framework for a major research program focusing on stress interactions of elevated UV-B radiation and increased carbon dioxide concentrations and their effects on crop species.

The goals of this program include:

1) Determine and understand the effects of increasing UV-B radiation alone and in combination with ozone on growth, development, yield and quality of selected species and cultivars.

2) Determine effects of increasing carbon dioxide on plant response to UV-B and ozone.

3) Determine effects of UV-B, ozone and carbon dioxide, as mediated through plant response, on selected components of rhizosphere microbial communities.

4) Determine how biotic and abiotic stresses affect plant response to UV-B, ozone and carbon dioxide.

The ARS will develop programs to study the effects of global climate change and will continue studying air pollution's impact on forests.

VI. ELECTRIC POWER RESEARCH INSTITUTE

A. INTEGRATED FOREST STUDY PROGRAM

The Integrated Forest Study is a program initiated by the Electric Power Research Institute to study nutrient cycling and carbon allocation in forest stands. Overall, the IFS project can be subdivided into four parts: atmospheric deposition (wet and dry), and ozone and carbon dioxide concentrations, throughfall and stem flow, vegetation structure and dynamics, and soil water and ion budgets. Three of the 20 sites are located in the Southeast, in Alachua County, Florida; Clarke County, Georgia; and Orange County, North Carolina. The site in Florida was initially established under a National Science Foundation grant. It focuses on canopy photosynthesis and internal allocation of carbon to growth and respiration in a mature, slash pine stand as water and nutrient availability are altered by fertilization treatments and drainage (to lower the water table). On four plots, detailed physiological and soil processes studies are being conducted under funding provided by the SCFRC. Meteorological measurements and pollutant concentrations are determined above, at the surface, within, and below the forest canopy.

B. RESPONSE OF PLANT TO INTERACTING STRESSES

The efforts are interdisciplinary and collaborative, involving scientists from the TVA, ORNL, Cornell University, USDA Forest Service, and Mississippi State University. The objectives of ROPIS-SOUTH are fourfold: (1) document the role of genotype in governing the response to ozone; (2) characterize the above-ground and below-ground growth responses to ozone, rainfall chemistry, and soil magnesium status (singly and in combination); (3) evaluate the edaphic and physiological basis for observed growth responses; and (4) develop and apply mechanistically-based models of loblolly pine to evaluate the responsiveness of this species to a range of environmental stress scenarios.

VII. NATIONAL COUNCIL OF THE PAPER INDUSTRY FOR AIR AND STREAM IMPROVEMENT

The National Council of the Paper Industry for Air and Stream Improvement (NCASI) was formed during the 1940's as the environmental investigative arm of the pulp and paper industry. Recent new initiatives are focusing on air quality/forest health, wildlife management, and forest wetlands management.

The Air Quality/Forest Health Program is guided by a Task Group of paper industry scientists and managers. The program has four goals:

1) Determine ambient air quality in commercial forest lands.

2) Define individual tree responses to ambient air quality.

3) Define impacts of ambient air quality on commercial forest productivity.

4) Define impacts of atmospheric deposition on forest soil productivity.

To accomplish its goals, the NCASI supports the Southern Commercial, Spruce-Fir, Eastern Hardwoods, and Western Conifer Research Cooperatives of the Forest Response Program. Other research efforts include individual-tree and stand modeling of air-pollution effects and the use of new technologies such as ^{11}carbon dioxide tracers and "chamberless systems" to quantify air quality effects on forest health.

VIII. DEPARTMENT OF ENERGY - Oak Ridge National Laboratory Oak Ridge, Tennessee

The Environmental Sciences Division of Oak Ridge National Laboratory has had a long-standing interest and involvement in evaluating responses of forested ecosystems to a wide variety of natural and anthropogenic environmental stresses. A key focus in this research has been the examination of multiple processes and pathways of response to provide a more complete understanding of both the mechanistic basis of responses observed, as well as the measured or expected levels of response. At a biogeochemical level this emphasis has led to a network of intensive study sites both on the ORNL Reservation as well as at many collaborating regional sites where budgets of inputs of wet and dry deposited pollutants to forested landscapes, movement and transformation of pollutants through the soil profile, and interactions with key nutrient species have been developed empirically. These data bases and study site, including historical inventories of soils and vegetation, as well as the models of mixed species forest growth and competition, represent potentially valuable resources for future studies aimed at evaluating the effects of environmental stress on southern forests.

ORNL studies in physiological ecology have had a similar integrated focus with emphasis on whole plant responses to environmental stresses, particularly key relationships between above-and below-ground systems influencing uptake and utilization of carbon, water, and nutrient resources. Current research on the physiological basis of slowing growth of red spruce at high elevations in The Smoky Mountains has examined photosynthesis, dark

respiration, carbon allocation, water relations, and foliar levels of chlorophyll, nitrate reductase activity, and nutrients in relationship to reduced growth observed in both sapling and mature trees at high elevations. The use of dendroecology to characterize long-term growth trends, evaluate growth relationships to local and regional site factors, and to explore key relationships between historical changes in soil chemistry and tree ring chemistry have been important tools in this process. Current collaborative research with the EPRI-sponsored Integrated Forest Study emphasizes interactions between soil cation availability, deposition of strong anions in precipitation, and tree physiological responses.

As a part of the Southern Commercial Forest Research Cooperative, ORNL has evaluated comparative growth response of 53 families of loblolly pine to ozone and acidic deposition. Comparative growth of roots and shoots and changes in carbon assimilation and allocation were initially emphasized. A significant adverse growth response of most families to ambient ozone levels has led during the past two years to continued efforts to evaluate growth responses of six families to ambient ozone levels in open-top chambers. A canopy level gas exchange system has been developed to evaluate responses of larger trees to ambient ozone and provides continuous measurements of exchange of carbon dioxide, water and ozone within the canopies of both sapling and larger trees. Dendrometer bands are also being used to evaluate site and atmospheric influences on the kinetics of growth of mature trees in managed stands. The 45 chamber field research site is currently being used to evaluate interactions between ozone, acid deposition, and soil magnesium levels on growth and physiology of loblolly pine. Other studies on the influence of elevated carbon dioxide on tree growth and physiology and a suite of coupled whole-plant physiological models of carbon, water, and nutrient utilization augment current research.

IX. NATIONAL PARK SERVICE

The Southeast region of the National Park Service (NPS) has assembled a Task Force on Global Climate Change. The goal of this working group is to develop a strategy for how the southeastern region will address the issue of climate change in an integrated way. The task involves defining what the problem is and identifying the appropriate mamagement strategy to deal with the problems that may occur.

A NPS project is now underway which will assess potential impacts on the 58 Park Service units in the Southeast. This project will identify the units, define potential threats (e.g., to biodiversity, wildlife habitat, rare and endangered species, sensitive communities), survey managers to identify the major threats to their units, and propose appropriate monitoring for these systems.

The NPS currently conducts visibility and air quality monitoring in a number of locations in the southeastern region, particularly in order to protect Class Wilderness Areas. The Park Service has also conducted surveys of probable air pollution injury to vegetation in a number of park units. Research on ecological effects, foliar injury, and trace elements is being conducted in the Great Smoky Mountain National Park, Everglades National Park, Big Cypress National Preserve, and Biscayne National Park. The NPS also participates in cooperative research with outside investigators (e.g., work on acidic deposition and nutrient cycling in the Smoky Mountains as part of the Integrated Forest Study).

LITERATURE CITED

Anderson, R.L., J. P. McClure, N. Cost, and R.J. Uhler. 1986. Estimating fusiform rust losses in five southeast states. South. J. Appl. For. 10:237-240.

Becwar, M.R., F.D. Moore III, and M.J. Burke. 1982. Effects of deletion and enhancement of ultraviolet-B (280-315nm) radiation on plants grown at 300 m elevation. J. Amer. Soc. Hort. Sci. 107:771-779.

Binkley, D., C.T. Driscoll, H.L. Allen, P. Schoeneberger, and D. McAvoy. 1989. Acidic Deposition and Forest Soils: Context and Case Studies in the Southeastern United States. Ecological Studies 72. Springer-Verlag, NY. 149 pp.

Brandle, J.R., W.F. Campbell, W.B. Sission, and M.M. Caldwell. 1977. Net photosynthysis, electron transport capacity, and ultrastructure of Pisium ativum L. exposed to ultraviolet-B radiation. Pl. Physiol. 60:165-169.

Brix, H. 1971. Effects of nitrogen fertilization on photosynthesis and respiration in Douglas-fir. For Sci. 17:407-414.

Brix, H. 1979. Effects of plant water stress on photosynthesis and survival of four conifers. Can. J. For. Res. 9:160-165.

Brix, H. 1972. Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. Can. J. Forest Res. 2:467-478.

Chameides, W.L., R.W. Lindsay, J. Richardson, and C.S. Kiang. 1988. The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study. Science 241:1473-1475.

DeBell, D.S., D.D. Hook, W.H. McKee, Jr., and J.L. Askew. 1984. Growth and physiology of loblolly pine roots under various water table levels and phosphorus treatments. For Sci. 30:705-714.

Flint, D.D, P.W. Jordan, and M.M Caldwell. 1985. Plant protective response to enhanced UV-B radiation under field conditions: leaf optical properties and photosynthesis. Photochem. Photobiol. 41:95-99.

Garner, J.B., T. Pagano, and E.B. Cowling. 1989. Critical assessment of the role of acid deposition and other airborne sulfur- and nitrogen-derived pollutants in the forests of eastern North America. Report to the Southern Commercial Forest Research Cooperative.

Gholz, H.L. and R.F. Fisher. 1984. The limits to productivity: Fertilization and nutrient cycling in coastal plain forests. E.L. Stone (ed.). In Forest Soils and Treatment Impacts, the Sixth North American Forest Soils Conference Proceedings, Knoxville, TN. pp. 105-120.

Johnson, D.W., D.D. Richter, H. Van Miegroet, and D.W. Cole. 1983. Contributions of acid deposition and natural processes to cation leaching from forest soils: a review. J. Air Pollut. Control. Assoc. 33:1036-1041.

Kinerson, R.S. 1975. Relationships between plant surface area and respiration in loblolly pine. J. Appl. Ecol. 12:965-971.

Kossuth, S.V. and R.H. Biggs. 1981. Ultraviolet-B radiation effects on early seedling growth of Pinaceae species. Canad. J. For. Res. 11:243-248

Kozlowski, T.T., ed. 1968. Water Deficits and Plant Growth. Vol. II. Plant Water Consumption and Response. Academic Press, Inc., New York. 333 pp.

Kozlowski, T.T. 1985a. SO_2 effects on plant community structure. In Sulfur Dioxide and Vegetation: Physiology, Ecology, and Policy Issues (W.E. Winner, H.A. Mooney, and R.A. Goldstein, eds.). Stanford Univ. Press, Stanford, CA., p. 431-453.

Kowlowski, T.T. 1985b. Tree growth in response to environmental stresses. J. Arboric. 11:97-111.

Kowlowski, T.T. and H.A. Constantinidou. 1986b. Responses of woody plants to environmental pollution. I. Sources and types of pollutants and plant responses. For. Abstr. 47:5-51.

Kramer, P.J. and T.T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, Inc. Orlando, FL., 811 pp.

Kress, L.W., H.L. Allen, J.E. Mudano, and W.W. Heck. 1989. Ozone effects on the growth of loblolly pine. In Proceedings, IUFRO Conference: Air Pollution and Forest Decline, Interlaken, Switzerland, 6 pp. (In Press).

Lefohn, A.S. and J.E. Pinkerton. 1988. High resolution characterization of ozone data for sites located in forested areas of the United States. J. Air Pollut. Control Assoc. 38:1504-1511.

Lister, G., V. Slankis, G. Krotkov, and C.D. Nelson. 1968. The growth and physiology of Pinus strobus L. seedlings as affected by various nutritional levels of nitrogen and phosphorus. Ann. Bot. (Lond.) 32:33-43.

Loomis, R.C., S. Tucker, and T.H. Hofacker. eds. 1985. Insect and Disease Conditions in the United States 1979-1983. USDA Forest Service Gen. Tech. Report WO-46. Forest Pest Management, State and Private Forestry. Washington, D.C. 93 pp.

Meadows, J.S., J.D. Hodges, R.G. Amundson, T.M. Hinckley, D.R. Houston, R.L. Edmonds, and G.L. Switzer. 1988. Effects of natural and airborne chemical stresses on growth and development of individual trees and forests. Final Report to Southern Commerical Forest Research Cooperative. 513 pp.

National Atmospheric Deposition Program. 1987. Annual Data Summary: Precipitation Chemistry in the United States. Fort Collins, CO. Colorado State University, Natural Resources Ecology Laboratory. National Atmospheric Deposition Program.

National Research Council. 1977. Effects of nitrogen oxides on vegetation. In Nitrogen Oxides. Washington, DC: National Academy of Sciences, pp. 437-585.

Reich, P.B. 1987. Quantifying plant response to ozone: a unifying theory. Tree Physiol. 3:63-92.

Reinert, R.A., S.R. Shafer, G. Eason, S.J. Horton, M.M. Schoeneberger, and C. Wells. 1988. Responses of Loblolly Pine Half-Sib Families to Ozone. 81st Annual Meeting of the Air Pollution Control Association, Dallas, TX. June 19-24, 1988. Paper No. 88-125.2, 14 pp.

Richter, D.D., P.J. Comer, K.S. King, H.S. Sawin, and D.S. Wright. 1988. Effects of low ionic strength solutions on pH of acid forest soils. Soil Sci. Soc. Am. J. (In Press.)

Sheffield, R.M., N.D. Cost, W.A. Bechtold, and J.P. McClure. 1985. Pine Growth Reductions in the Southeast. USDA Forest Service Resource Bulletin SE-83. Southeast Forest Exp. St., Asheville, NC. 112 pp.

Sisson, W.B. and M.M. Caldwell. 1976. Photosynthesis, dark respiration and growth of Rumex patientia L. exposed to ultraviolet irradiance (288-315 namometers) simulated a reduced atmospheric ozone column. Pl. Physiol. 58:563-568.

Stone, E.L., C.A. Hollis, and E.L. Barnard. 1982. Boron deficiency in a southern pine nursery. South. J. Appl. For. 6:108-112.

Sullivan, J.H. and A.H. Teramura. 1988. Effects of ultraviolet-B irradiation on seedling growth in the Pinaceae. Amer. J. Bot. 75(2):225-230.

Swank, W.T. and J.B. Waide. 1988. Characterization of baseline precipitation and stream chemistry and nutrient budgets for control watersheds. In Forest Hydrology and Ecology at Coweeta. W.T. Swank, D.A. Crossley, Jr. eds., pp. 57-79. Ecological Studies, Vol. 66. New York: Springer-Verlag.

Teramura, A.H. 1980. Effects of ultraviolet-B irradiance on soybean. I. Importance of photosynthetically active radiation in evaluating ultraviolet-B irradiance effects on soybean and wheat growth. Physiol. Pl. 48:333-339.

Teskey, R.O., J.A. Fites, L.J. Samuelson, and B.C. Bongarten. 1986. Stomatal and nonstomatal limitations to net photosynthesis in Pinus taeda L. under different environmental conditions. Tree Physiol. 2:131-142.

Teskey, R.O. and T.M. Hinckley. 1986. Moisture: Effects of water stress on trees. In Stress Physiology and Forest Productivity (T.C. Hennessey, P.M. Dougherty, S.V. Kossuth, and J.D. Johnson, eds.), p. 9-33. M. Nijhoff Publ., Dordrecht, Holland.

Tevini, M. and W. Iwanzik. 1983. Inhibition of photosynthetic activity by UV-B radiation in radish seedlings. Physiol. Pl. 58:395-400.

Tolley, L.C. and B.R. Strain. 1984a. Effects of carbon dioxide enrichment and water stress on growth of Liquidambar styraciflua and Pinus taeda seedlings. Can. J. of Bot. 62:2135-2139.

Tolley, L.C. and B.R. Strain. 1984b. Effects of carbon dioxide enrichment on growth of Liquidambar styracifluam and Pinus taeda seedlings under different irradiance levels. Can. J. of For. Res. 14:343-350.

Treshow, M. 1970. Environment and Plant Response. McGraw-Hill Book Co., New York. 422 pp.

USDA Forest Service. 1969. A Forest Atlas of the South. USDA Forest Serv., South. Forest Exp. Stn., New Orleans, LA, and USDA Forest Serv., Southeast. Forest Exp. Stn., Asheville, NC. 27 pp.

USDA Forest Service. 1988. The South's Fourth Forest: The Opportunities to Increase the Resource Wealth of the South. USDA Forest Service Miscellaneous Publication No. 1461. Washington, D.C. 28 pp.

U.S. Environmental Protection Agency. 1982. Air Quality Criteria for Particulate Matter and Sulfur Oxides. Research Triangle Park, NC. U.S. Environmental Protection Agency; EPA Report No. EPA-600/8-82-026.

U.S. Environmental Protection Agency. 1986. Air Quality Criteria for Ozone and Other Photochemical Oxidants. Research Triangle Park, NC. U.S. Environmental Protection Agency; EPA/600/8-84/020bF.

Van Lear, D.H. and J.E. Douglass. 1982. Water in the loblolly pine ecosystem--eastern region. In Proc. Symp. Loblolly Pine Ecosystem (East Region), Dec. 8-10, 1982, Raleigh, NC (R.C. Kellison and S. Gingrich, eds.), p. 285-296. School of Forest Resources, NC State University, Raleigh, NC and USDA Forest Serv., Southeast. Forest Exp. Stn., Asheville, NC.

Wells, C. and L. Allen. 1985. When and where to apply fertilizer: A loblolly pine management guide. USDA Forest Serv. Gen. Tech. Rep. SE-36. Southeast. Forest Exp. Stn., Asheville, NC. 23 pp.

Woodman, J.N. and C. Sasser-Furiness. 1989. Potential effects of climate change on U.S. forests: Case studies of California and the Southeast. US EPA Office of Policy, Planning, and Evaluation. 36 pp.

Zahner, R. 1962. Terminal growth and wood formation by juvenile loblolly pine under two soil moisture regimes. Forest Sci. 8:345-352.

Zahner, R. 1968. Water deficits and growth of trees. In Water Deficits and Plant Growth. Vol. II. Plant Water Consumption and Response (T.T. Kozlowski, ed.), pp. 191-254. Academic Press. New York.

USDA Forest Service. 1988. A Forest Atlas of the South. USDA Forest Serv., South. Forest Exp. Stn., New Orleans, LA, and USDA Forest Serv., Southeast. Forest Exp. Stn., Asheville, NC. 17 pp.

USDA Forest Service. 1988. The South's Fourth Forest: The Opportunities to Increase the Nation's Timber Supply in the South. USDA Forest Service Miscellaneous Publication No. 1463. Washington, D.C. 38 pp.

U.S. Environmental Protection Agency. 1982. Air Quality Criteria for Particulate Matter and Sulfur Oxides. Research Triangle Park, NC. U.S. Environmental Protection Agency, EPA Report No. EPA-600/8-82-029.

U.S. Environmental Protection Agency. 1986. Air Quality Criteria for Ozone and Other Photochemical Oxidants. Research Triangle Park, NC. U.S. Environmental Protection Agency, EPA/600/8-84/020bF.

Van Lear, D.H. and J.E. Douglass. 1983. Water in the loblolly pine ecosystem: eastern region. In Proc. Symp. Loblolly Pine Ecosystem (East Region), Dec. 8-10, 1982, Raleigh, NC (R.C. Kellison and S. Gingrich, eds.), pp. 285-296. School of Forest Resources, NC State University, Raleigh, NC and USDA Forest Serv., Southeast. Forest Exp. Stn., Asheville, NC.

Wells, C. and L. Allen. 1985. When and where to apply fertilizer: A loblolly pine management guide. USDA Forest Serv. Gen. Tech. Rep. SE-36. Southeastern Forest Exp. Stn., Asheville, NC. 23 pp.

Woodman, J.N. and C. [illegible]. 1989. Potential effects of climate change on U.S. forests: Case studies of California and the Southeast. US EPA Office of Policy, Planning, and Evaluation. 28 pp.

Zahner, R. 1962. Terminal growth and wood formation by juvenile loblolly pine under two soil moisture regimes. Forest Sci. 8:345-352.

Zahner, R. 1968. Water deficits and growth of trees. In Water Deficits and Plant Growth. Vol. II. Plant Water Consumption and Response (T.T. Kozlowski, ed.), pp. 191-254. Academic Press, New York.